Thornton and Tully's Scientific Books, Libraries and Collectors

Edited by Andrew Hunter

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Fourth edition, considerably revised, and rewritten

Edited by Andrew Hunter

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Introduction

It is more than a quarter of a century since the third edition of Thornton and Tully's *Scientific Books, Libraries and Collectors* and its *Supplement* were published. The companion volume on *Medical Books* (the first on the scene) went into its third, revised, edition in 1990. This new edition of *Scientific Books* follows the precedent of its companion in now being a team effort, and departs still further from the original format, without, I trust, betraying its spirit. Involving changes outlined below, the aim has been to avoid the status of 'semi-readable' (bestowed by Sir Geoffrey Keynes upon the first edition of the *Medical Books*) and to become, while retaining the character of a work of reference, something more narrative and argumentative. Fewer books are therefore named, or listed, and in this sense the earlier editions are not replaced; but it is hoped that the detailed discussion of certain ones will prove equally useful, and perhaps more enlightening. The book trade moves closer to centre stage.

In that quarter of a century changes in the nature of scientific publishing have been profound, and the landscape of the historiography of science has altered dramatically. On the one hand, the dominance of the journal is now under threat from electronic media, which in itself poses interesting questions for future librarians and historians. Moreover, if 90 per cent of scientists (the definition of this word is considered at several points in the volume) who have ever lived are reckoned to be alive – and publishing – today, it is clearly not possible to survey them either comprehensively or in due proportion. On the other hand, the appearance of the *Dictionary of Scientific Biography*, and numerous smaller or more specialized dictionaries, '*Timetables*', '*Breakthroughs*' and the like (none of them, unfortunately, bibliographical), have wonderfully increased the availability and accessibility of information about scientists and the history of science. A bibliographical bedrock such as William Brock's chapter on scientific bibliographies is not easily encountered elsewhere, however. History of science is now a fully fledged academic industry, and it is hoped that this volume will serve to direct its workers to fuller appreciation of the myriad forms of published material: as it were, the testimony of the books.

It was decided to restrict the scope of this new edition to the history of science and to make no attempt to cover current scientific research or libraries

which cater to that research. This has allowed more space for the libraries, and especially the collectors, of the title. All the same, there is a new chapter on scientific publishing in the twentieth century. The debate about publishing (about texts and readers, about contexts and ownership) has moved on, and the present volume seeks, in the differing approaches of the contributors, to provide authoritative portraits of scientific publishing through the ages. Two custodians of special collections begin the story, and the two concluding chapters examine the origins of scientific book collections, the collectors, their motives, and the fate of their collections.

In a single volume a satisfactory conspectus of worldwide scientific endeavour cannot be given (the late Joseph Needham's *Science and Civilisation in China*, CUP, still continuing, already occupies seven in ten volumes, and dozens of volumes are devoted to the correspondence of a single scientist). Therefore the science that the book is concerned with is essentially the science of Europe, or the West; still, an effort has been made to expand the vista of the earlier editions, notably by the inclusion of a chapter on Islamic science.

I am deeply grateful to many people (alas, too many to be all mentioned here) who have helped me and encouraged me in the preparation of this work, first and foremost to the contributors, who have all contributed so much more than their essays. Special thanks are also due to Gavin Bridson, John Henry and David Knight. To have become immersed in scientific books I am entirely beholden to Bernard Quaritch Ltd.

Andrew Hunter

Chapter One

The Scientific Book as a Cultural and Bibliographical Object

Henry E. Lowood and Robin E. Rider

As the twentieth century draws to a close, increasingly rapid electronic communication is challenging the viability of all print media and has accelerated change in the nature of scientific discourse. In that discourse, the printed monograph, at first central, gave way long ago to journals and paper preprints. But now scientific disciplines are moving quickly to embrace electronic modes of publication – so much so that some academic scientists never enter the traditional research library – with important consequences for both libraries and the printed volumes that fill them. It is thus timely to remind ourselves of the roles played first by books, and then by periodicals, in the emergence of modern science.

Printed books and journals have a long track record in the service of the natural sciences. Certainly, by the end of the seventeenth century, printed books and journals had demonstrated their ability to deliver information, preserve knowledge, and enhance scientific communication. In this sense, the printed book of nature can, and should, be considered a product of the Scientific Revolution, as much so as the telescope or the experiment. At the same time, printed books are artefacts of typographic practice. We write here both as historians and librarians, responsible for building library collections as well as using them, and we also share common interests with collectors and booksellers, whose marketplace we all frequent. The printed book of science is a cultural and bibliographical object sited at the intersection of printing and publishing history with history of science. To set in context our view of the scientific book, we begin by considering general topics of interest primarily to librarians and collectors with special interests in the history of science publishing. We then

identify two broad, yet salient issues surrounding the scientific book that cut across the chronological divisions of the chapters that follow.

The first issue will be one of control: who made the scientific book? And what are the implications of that form of control vis-à-vis the contents of a scientific book, its reception, historical significance, and interest for collectors?

Second, we will look at what is often considered a standard 'property' of the printed book of science, namely, its 'fixity' as a source of information. Elizabeth Eisenstein has argued that 'the fact that identical images, maps and diagrams could be viewed simultaneously by scattered readers constituted a kind of communications revolution in itself'.[1] Indeed, it became possible for printed scientific data to be 'duplicated without being blurred or blotted out over the course of time'.[2] The notion of fixity focuses our attention on the standardization of texts and images in the printed book, but it also suggests the question of mutability and malleability. Indeed, the idea that fixity might be a defining characteristic of printed books implies a tension between the unique and the multiple.[3] It also implies the possibility of an impermanent grey literature that borrows from technologies of print culture but compromises stability of content. Together these contrasts and tensions inform our assessments of the intellectual and historical value of printed texts and individual copies of them.

Scientific libraries as context

The hallmarks of a modern scientific library are its periodical collection and an ongoing programme of serial subscription, supplemented by current monographs, textbooks and reference titles. Although institutional libraries of all stripes now face (as they have faced in the past) challenges to their continued existence from budget cuts, soaring prices, space pressures and new electronic media, their past acquisitions remain a tangible source of strength. Items now seen as eminently collectible – Einstein's articles in the *Annalen der Physik for* 1905, Watson and Crick's *The Double Helix*, nineteenth-century illustrated journals, or hand-coloured works of natural history, for example – were often acquired by libraries at the time of publication and sat on open shelves for years thereafter. Whatever the rarity or importance of such individual gems, the value of such a collection builds on the steady accumulation of mainstream publications to support research programmes. In such libraries created for intensive use, generations of readers have by now left their marks. Signs of use and abuse, as well as institutional practices such as rebinding, ownership stamping and discarding advertisements, may be seen initially as compromising research value – or when titles reach the antiquarian market, as reducing their appeal to collectors. Similarly, libraries and archives typically avoid some categories of publications now desirable to collectors of modern (especially twentieth-century) science – notably reprints and offprints of 'classic' papers – viewed as duplicating the contents of formal publishing venues such as journals. Even

when a collection of reprints is offered as part of a scientist's correspondence and papers, it is generally not retained intact.

In most academic libraries or library systems, the value of scientific publications changes, in that they gradually serve less the current needs of working scientists than primarily historical research. At this stage, responsibility for these works often passes intellectually and physically from dedicated scientific collections to general research libraries or departments of special collections. As part of this transition, curators and bibliographers in the history of the book, rare book librarianship or the history of science reassess these publications in the context of their historical or bibliographical value; they also acquire additional antiquarian or rare materials from the book market for a research community ranging from historians to bibliophiles, as well as scientists. Not only are the content, importance and research value of the books themselves evaluated anew, but the evidence of previous ownership, use, distribution and publication history acquires fresh meaning. New cataloguing standards, including more detailed description and the addition of 'access points', play important roles in providing bibliographic indexing and retrieval of information that provide clues for these reappraisals.

Libraries, like private collectors, do not have limitless resources. Librarians thus have to develop criteria for selectivity with respect to new acquisitions. 'High spots', for example, tend to appeal less to librarians than to private collectors. Libraries rarely discard non-duplicate titles, unless under severe economic pressure, and build collection strengths as an accumulation of the efforts of many librarians. These generalizations are especially true for libraries so fortunate as to already possess many seminal works in first or most significant editions and, less fortunately, for those lacking funds to support energetic acquisitions programmes. For antiquarian books of science, as for modern literary firsts, some librarians will buy a later edition or an indifferent copy if they anticipate reader interest primarily or solely in the text – say, by a local faculty member or students. In some cases, selection of a later edition 'much enlarg'd' may prove fortunate by providing more grist for the scholarly mill.[4] Downplaying collectibility in favour of content reflects the priorities of research programmes, budgetary constraints, convictions, or some combination of these motives, though at the same time curators of library collections are acutely aware of the significance of printed books as artefacts, criteria of value, rarity, preservation needs, and potentially fruitful collecting tangents.

Research libraries and those who benefit from them enjoy larger networks and bases of information than do many collectors. And their rare book acquisitions in scientific fields acquire significance and context from broader institutional collections as well as numerous disciplinary and multidisciplinary lines of research. The richness of book collections in academic library systems, even if they are distributed among subject-oriented branches, locked cases and special collections departments, permits, if not encourages, cross-disciplinary comparison. For example, typographic practice of a given era – and how it applied to

books of natural science – may be seen more clearly with books of many different subjects to hand. Such comparison can be particularly revealing with regard to the relationship among author, text and typographic culture. Publishing programmes were scarcely limited to science or natural history. And the recycling and retouching of woodcuts and engravings[5] may mean that natural history illustrations have another, decorative life with weaker links to the non-scientific texts they came to adorn. A researcher would need to see more than natural history books to test such a hypothesis; generally speaking, only research libraries or networks of such libraries provide collections of sufficient breadth, depth and quality to support such enquiries.

Changing approaches to the history of the book, attentive to the materiality of the text, reader response, canon formation, and other sociocultural meanings of books, are prompting historians and librarians to redefine existing collections in light of new scholarly interests. For instance, concern for the response of historical readers may lend new significance to ownership marks and clues, annotations, and other ways in which the owner or reader of a book makes it his 'own'.[6] As noted above, special cataloguing practices record this information and make it available through on-line catalogues; with the availability of computer-based bibliographic searching tools, these data are certain to stimulate new research interests. Studies of use based on physical traces of use in books are not neatly congruent with the traditional demands of many collectors for pristine volumes with noble provenance, though both approaches may benefit from one another.

The collections of individual collectors enjoy a dynamic, personal character that research libraries – with their emphasis on cumulation, breadth and multiple research vectors – generally have difficulty creating. Collectors trade up copies, refine or change the focus of their collecting, and jettison earlier collections in favour of new interests. Libraries may acquire 'better' copies of existing holdings, and happily so; but de-accessioning inferior copies, let alone disposing of collections in order to launch new ones, is fraught with difficulties for special collections libraries. Where some individuals and some public lending libraries weed their collections with relative ease, most rare book collections are blessed (or afflicted) with an aura of permanence.[7]

One should not, however, overstate the distinctions between libraries and private collections. Collectors do, though not as often or as quickly as librarians would like, become donors. Or they sell their collections, en bloc or piece by piece, through dealers or auctions, to fortunate libraries. Libraries can plant the idea of becoming a collector in the first place, and can also provide guidance with respect to the marketplace and sources of bibliographic information. The generosity of collectors can also extend to scholars, as when collectors make their prize bibliographic possessions available for scholarly research. All camps – librarians, historians, collectors and book dealers – can benefit from the expansion and sophistication of on-line library catalogues and the increasing use of the Internet by book dealers. So too can they benefit from recent scholar-

ship on history of the book, history of authorship, and history of reading. Some of the most important lessons of that scholarship have illuminated the problematic relationship between authors and publishers.

The author and typographic culture, or, A matter of control

It is clear from scholarship on the first two centuries after Gutenberg's invention that authors – whether individually or collectively – had little control over the appearance of their work in print. What control they exercised over the creation of texts for publication began to dissipate as soon as their manuscripts reached the printer's hands. This was as true for scientific texts as it was for literature or philosophy.

Control in the first instance resided in those with access to the means of production, which for early printing technologies meant printers and publishers. A master printer owned the printing press itself and cases of movable type (generally purchased at considerable cost from a typefounder), and journeymen typesetters and pressmen possessed the expertise to produce a creditable printed page. None of these lay within the possessions or ken of the average author. Then whoever made the investment in paper for an edition – either the master printer or, at one remove, the publisher - exercised another, decisive form of control over the publication of a given text. Other agents of typographic culture, including editors, illustrators, blockcutters, and engravers, also played a crucial role in the production of printed texts and images. Thus access to – or indeed command of – relevant technologies privileged the agents of typographic culture when it came to controlling the artefact we know as the early printed scientific book. As Martin Lowry has pointed out in connection with Aldus Manutius, 'authors not only condoned, but expected, a large amount of intervention from their publishers.[8] A modern reader, accustomed to practices and privileges of copyright, may be surprised to learn of the full measure of the publishers' economic and intellectual control over these books, often at the expense of the authors' interests or intentions.

The role of authors

A modern linkage between authorship and notions of intellectual/economic ownership did not begin to emerge in the sciences (or in other disciplines) until the end of the seventeenth century. The newly established scientific academies legally empowered to authorize the printing of books, emerging notions of copyright, increasing technical specialization in the sciences, and the growing prestige of authors as creative agents all played roles in this transformation of the status and economic standing of authorship.

Before the 18th century, states and principalities often granted limited legal protection against unauthorized reprinting within specific jurisdictions and peri-

ods of time. Typically, it was the printer or publisher of a book – and not the author – who received a legal privilege granting an exclusive right to publish a given text. That privilege was intended to protect the printer/publisher's material investment of capital and labour in producing the book, rather than to guard the creative rights flowing from authorship. In the case of Pierre Belon's *Observations de plusieurs singularitez et choses memorables* (1553), the printer, Gilles Corrozet, feared that 'after the costs he will meet in order to print this volume, other printers would want to print from *his* copies ... and in this way will frustrate his labors and expenses.' So Corrozet obtained a privilege affording him six years' protection against competitors, granted in the name of the king of France, who desired 'all good books to be published [mettre en lumière] for the public good'. According to the privilege, no other printer within the 'kingdom, country, territory, and seigneuries' would be allowed to print Belon's text without Corrozet's permission, upon penalty of imprisonment.[9] Generally, this form of privilege became the norm on the Continent by the end of the sixteenth century. In England, a system of registration managed by the Company of Stationers evolved along different lines and eventually served to record publications, control printers, and protect, also in a limited way, the publishers' investment and rights in a printed work. Only rarely did these legal declarations acknowledge the rights of authors.[10] And even when privileges were enforced against pirated editions, there were authors, Galileo among them, who still considered their words inadequately protected and themselves poorly recompensed.[11]

Early printers and publishers were inclined to publish texts of proven worth or marketability, which in the first instance led them to manuscript titles with established readerships. Not only did the well-established market for manuscripts drive the choice of texts, but norms and conventions borrowed from manuscript production were preserved in print. In many cases authors were not party to the conversion. In choosing to produce the first printed edition of Euclid's *Elements*, for example, Erhard Ratdolt knew he could expect steady sales from this sturdy classic, and sought to satisfy readers who expected to see their Euclid in the form made familiar by manuscripts. Ratdolt thus borrowed a well-worn translation of the Middle Ages, and carried over manuscript conventions into print: larger letters for the theorems, smaller for the proofs, division of the texts into manageable units, highlighting and ornamenting textual passages, and preserving the relationship of text and diagrams. In this first printed edition of Euclid, the text was derived from the medieval translation of Adelard of Bath, who worked from an Arabic translation, as later revised by Campanus of Novarra in the 13th century. Throughout the sixteenth century, novelty, at least in text, was not necessarily desirable. But while the text was perhaps a pale reflection of Euclid's, the printer Ratdolt left his mark in the nearly 600 innovative diagrams, the first to appear in a printed geometry book. Renaissance printers catered to an enduring market for retrograde works like the *Sphaera Mundi* of Sacro Bosco, and often as not embellished these old texts with solidly conventional models in woodcut form; some tried to capture more

of the market, however, by displays of typographic verve or by commissioning fresh images drawn from 'true life'.[12]

In some instances, business sense and scholarly instincts went hand in hand. The work of the Aldine press, and that of other scholar-publishers of the Renaissance, make clear the importance of printing to humanist projects for the recovery and restoration of ancient learning; indeed, there was a good fit between such intellectual enterprises and the ethos of typographic culture. Moreover, the editorial impulse behind many projects in this tradition encouraged close working relationships between author-editors and printer-publishers, who together paid careful attention to such practical matters as the review of proofs.[13] These humanist programmes, of course, covered a broad range of ancient learning, including scientific texts of Euclid, Dioscorides and Aristotle.[14]

As we have noted, the 'intellectual property' of authors as residing in their words was poorly protected in the sixteenth and seventeenth centuries. When living writers encountered their texts in print they often claimed their interests were ill-served. Well into the seventeenth century, their complaints testified to the disaffection, even antagonism between many contemporary authors, on the one hand, and printer-publishers, on the other. In part, this distance reflected the survival of patronage-oriented authorship, which emphasized the rewards of social status and reputation over cash remuneration tied to prospective sales. Authors produced texts and then published them as a way to glorify patrons; dedications and the distribution of gift copies speak to this practice, common among both scientific and non-scientific authors. The economic system of publication based on 'intellectual property' rights and the legal mechanisms of authorization (by an author!) to publish that we today take for granted were neither immediate nor obvious consequences of the invention of the printing press. The modern system of compensation for authorship emerged only in the eighteenth century, occasioned by, among other developments, the Copyright Act of 1709 in Great Britain, the growth of the reading public, and a new cultural value of authorial creativity.[15]

The case of William Harvey shows clearly how limited was an author's control over production of his texts in print. Harvey valued the collective judgement and assent of his colleagues and thus repeated his experiment on the circulation of the blood many times before the College of Physicians in London. His little book on the subject, *De Motu Cordis*, appeared in print once Harvey felt confident that his fellow physicians would back his ideas. As he wrote later about the publication of his *Anatomical Exercises* (the first English translation of *De Motu Cordis*), 'we have at last let it out to open view in this little book; which unless it were pass'd through your hands, I could hardly hope that it would come abroad entire and safe, since I can call most of You, being worthy of credit, as witnesses of those observations from which I gather truth, or confute error, who saw many of my Dissections, and in the ocular demonstrations of these things which I here assert to the senses, were us'd to stand by and assist me.'[16]

Yet Harvey was to learn that carrying his discoveries beyond the circle of direct witnesses and into open view posed new challenges. Both the first and later editions of William Harvey's pioneering work were printed carelessly and marred by numerous errors. For the first edition, he had chosen as his publisher William Fitzer, an English printer then working in Frankfurt am Main. That first edition suffered from the introduction of well over 100 typographical errors, perhaps due to Harvey's poor handwriting and his disinclination to read proofs; the errata were not published with the book; many copies lacked the leaf with Harvey's important dedication to King Charles II; and, finally, the engravings depicting the valves of the arm were only rough adaptations from another work, Fabricius' De *Venarum Ostiolis*, published a quarter-century earlier.[17] Subsequent editions offered few improvements. The sparse illustrations in the original were copied, reduced, recopied and occasionally missing altogether; and the second and third editions coupled Harvey's text with passage-by-passage refutations by Parisianus. Imperfect impressions, scrambled paginations and other errors led to continued misreadings of Harvey's text a quarter-century after his successful demonstration experiments in London. Small wonder that Zacharie Wood waxed bitter in justifying yet another try in his preface to the *Anatomical Exercises* of 1653: 'To this purpose we have again set forth Harvey's *Anatomicall Exercise*, which in the year 1648 was set out at Francfort, very faulty by the fault of the printer, which the author oft complain'd of, finding that the calumnies of his reprehenders had their beginning from thence, who not understanding what he said, did take them ill, and endeavour'd to traduce him publickly.' Now every effort had been expended to issue an edition 'mended and restored', claimed Wood. Even so it contained many uncorrected printer's errors, including at least one whole passage of garbled text. It is not surprising, therefore, that Harvey was said 'not [to] trust other mens writings, but his own faithfull eys, the truest reporters of Anatomy ...'[18]

Distrust of printers was by Harvey's day a seasoned tradition. The freedom with which academic publishers reprinted and reformatted books geared for university use, for example, often played havoc with original pairings of scientific texts and illustrations, such that both information and coherence were lost. Equally common was the metaphor of the philosopher who rejected books (faulty typography and all) in favour of looking directly at nature. Such scepticism about the value of printing and books, however, should not lead us to underestimate the importance scientific authors attached to the control of their published works. Securing the full benefits of the 'preservative powers of print' and the 'rigid visual fixity' of printed books would help to assure the accuracy of scientific information and promote adherence to existing and emerging conventions for presenting scientific arguments and evidence. But it would also require solutions to a number of practical problems that vexed authors of both scientific and non-scientific books.[19]

For some, close supervision of the process of publication suggested itself as the best way for an author to maintain control over the printed product. The

assertiveness of some scientific and mathematical writers provides instructive exceptions to the rule that most authors ignored typographical matters and left them to their publishers. For the first printed English translation of Euclid's *Elements*, the translator, Sir Henry Billingsley, and the author of its extravagant introduction, John Dee, inspected newly printed sheets, lest their intentions as authors or translators be misread; when they found typographical errors, they required the printer to print up corrections and paste them onto the sheets. As the sheets comprising his master work on the magnet emerged from the press, William Gilbert, physician to the English monarch, found more and more typographical errors, and tried to correct them by hand. What resulted were copies of *De magnete*, all printed and essentially the same, to be sure, but with quite different patterns of corrections in the author's hand.[20]

The conversion of hand-drawn scientific illustrations into printed images could be as laborious and problematic an undertaking as turning manuscripts into printed texts. Botanical woodcuts, for example, ranked among the finest achievements of the books' arts by the end of the sixteenth century, but the best examples required extraordinary teamwork among authors, illustrators and publishers, and proved an expensive undertaking. When authors thanked rather than cursed their publishers, they usually paid tribute to the cost of illustrations. In the introduction to his *Kreütterbuch* (1577), Hieronymus Bock expressed his gratitude to printers such as Michael Isingrin in Basel and Christian Egenolph in Frankfurt am Main for 'sparing neither expense nor effort' in commissioning woodcuts for the illustrated herbals they printed.[21] Yet, even when great care was lavished on original editions filled with oversized, detailed images, printer-publishers who put out later editions often altered the illustrations to suit their purposes. In so doing they compromised the standards set by the original project, as well as the intentions of the author.

A case in point is the famous herbal of Leonhart Fuchs, first printed at Basel by Isingrin in 1542. For the first edition, a team of two artists and a wood engraver prepared depictions of some 500 plants; full-page illustrations reflected their painstaking efforts, celebrated by a woodcut in the volume that showed Albrecht Meyer drawing from nature, Heinrich Füllmaurer drawing onto a woodblock, and Veit Ruldolf Speckle cutting a woodblock. This extraordinary woodcut was perhaps the earliest such recognition for a team of scientific illustrators, with its depiction of the intermixed roles of artist and scientist, of observation and representation. The herbal became one of the most popular descriptions of useful plants, with at least a dozen editions and translations printed between 1542 and 1550, beginning with a slightly augmented German edition in 1543. In 1545, a cheap octavo edition of the illustrations carried reduced copies, in reverse, of the woodcuts resized to fit the smaller format, but by then Fuchs' direct involvement with the project had ceased. While it may be assumed that handier editions served botanical excursions better than the weighty folio edition, Edward Lee Greene considers the 1545 octavo edition to have been published 'as if in condescension to the class of the unlettered', with the

illustrations so 'greatly reduced in size as to be of little use'. It was a successful edition, with another issue printed that same year, but by then Fuchs' direct involvement with the project had ended. Without the participation of author and artists, editions published over the next decade, primarily in France, cut corners. One edition printed at Paris for the faculty of medicine included only Fuchs' descriptions and commentaries and lacked images entirely. The two editions published by Arnoullet at Lyon in 1550 and 1551 (the first, a translation into French, and the second, a new Latin edition) provided only cramped quarters for the illustrations: up to three on a page, recopied for the smaller octavo format. Arnoullet's editions compromised botanical integrity, as flowering parts disappeared, leaves lost their veins, and other details were sacrificed. The next edition of 1555, a small pocketbook, once again dispensed with illustrations altogether.[22]

In the emerging scientific literature of the sixteenth and seventeenth centuries, the misgivings of authors with respect to the production and reproduction of texts and images contributed directly to new mechanisms and institutions for publication in fields such as natural philosophy, natural history, medicine and mathematics. As we note below, authors like Tycho Brahe, following the fifteenth-century lead of Regiomontanus, chose to print their own works.[23] Others, when illustrations proved crucial to their books, elected not merely to supervise the artists, blockcutters or engravers of typographic culture but instead to rely on their own talents. Johannes Hevelius, for example, drew and engraved the plates for his own works, and served as his own publisher.[24] [see plate 3]

These examples highlight just a few of the challenges of publishing scientific texts and images, of ensuring the accuracy of printed scientific books and of exercising intellectual and even financial control over the process of publication. In the sixteenth and seventeenth centuries, some individual authors were successful in controlling process and product. By the end of the seventeenth century, however, the combined efforts of new scientific institutions in England and on the Continent played an even greater role in controlling publication. They determined conventions for the presentation of information and argumentation in print and thereby safeguarded emerging notions of the importance of authorial and editorial control by the natural philosophers, astronomers, mathematicians and others who constituted their membership. The forms and practices they devised have proved durable and influential.

Early scientific institutions

The issue of control of publishing came to the fore in two of the premier institutions of early modern science, the Royal Society of London and the Royal Academy of Sciences (or Paris Academy). Each seized upon print to promote the work of science; in doing so each benefited from a royal grant of publishing privileges. The Royal Society's original charter, granted in August 1662, ceded to the Society the right to appoint 'one or more booksellers or printers who

were to publish such matters and concerns pertinent to the society.'[25] Equipped with this right of publication, which lay outside the usual realm of control exercised by the Stationers' Company in England, the Royal Society forged a publishing programme that required attention to many details of printing, publishing and bookselling. Its relationships with the practitioners of typographic culture were coloured by a central institutional objective: dissemination of knowledge generated or approved by the Society. To achieve this objective, the Society sought to control the quantity, quality and distribution of publications carrying its name or imprimatur. For instance, it ordered the 'making and publishing' of a catalogue of the Society's museum of 'natural and artificial rarities'; the task fell to Nehemiah Grew, and the finished catalogue documented the Society's role in its production.[26]

The matter of Society control over reports of its own activities also proved to be a complicated matter. The Society first gave instructions for the publication of the *Philosophical Transactions* in March 1664, less than two years after the original charter to the assembly. Each issue of the *Philosophical Transactions* was to be 'composed by Mr. Oldenbourg' (that is Henry Oldenburg, secretary of the Society) 'if [he shall] have sufficient matter for it', then reviewed by specified members of the Society and published by the 'printers to the Royal Society', John Martin and James Allestrey.[27] As secretary, Oldenburg assumed responsibility for the Society's correspondence, and the *Philosophical Transactions* evolved under his editorship as public extension of his correspondence. It was thus as much a private as a corporate enterprise. Indeed, as editor of the *Philosophical Transactions*, Oldenburg assumed the financial risk for its publication, and fought bitterly with the official printers of the Society over press runs, price and other issues. Plague and fire disrupted publication schedules, and Oldenburg's death in 1677 led to another gap in publication, only partially filled by Robert Hooke's *Philosophical Collections*.[28] Eventually the *Philosophical Transactions* were revived, and successive secretaries of the Royal Society filled Oldenburg's role as editor through the volume for 1750 (volume 46), after which a committee of the Society oversaw publication.[29] The longevity of the *Philosophical Transactions* not only reflected the institutional life of the Society, but it also set an example for the relatively rapid publication of short scientific reports and letters, a mode of publication that would become increasingly important for the sciences over the course of the 18th century.

In its earliest years the Paris Academy espoused an ideal of anonymous collective publication, but changes in its duties and privileges in 1699 reflected gradual abandonment of this ideal. The regulation of 1699 obliged the Academy to examine any work that a member proposed to have published; approval required a complete reading in the Academy's meetings, or at least a favourable report by the subcommittee charged with review of the manuscript. A member could only use the title academician in his writings if the work had received the Academy's approval.[30] Among the important privileges enjoyed by this royal academy as a body was that of publication independent of the general system of

court-appointed censors. In view of this special position granted by the Crown, academicians worked hard to control the quality of scientific books and to protect the Academy's image as expressed through its publications.

For the Royal Society, the *Philosophical Transactions* fitted in with a Baconian scheme of a collective effort to increase the sum of human knowledge; hence the desirability of frequent and prompt publication aimed at a wide audience. At the same time, despite its role in broadcasting results of its members' work and of communications to them, the Society kept a certain distance from official sponsorship of the journal. Although the Society's secretary edited the *Philosophical Transactions*, the Society, at least until the mid-eighteenth century, avoided endorsing the contents. The Paris Academy of Sciences, by contrast, aimed above all at creating a record of its collective accomplishments through the *Histoire*, an annual publication required by the Crown, and the polished, considered *Mémoires*. These latter were written by individual (paid) members of the Academy, reviewed by the assembly, and issued together with the *Histoire*. Despite these differences, the Royal Society competed with the Paris Academy of Sciences in publishing as in other activities. As Christiaan Huygens of the Paris Academy wrote to the Society's secretary in London, 'Mr. Cassini has shown us a manuscript copy of Malpighi's book, and if it had not been printed with you, it would very readily have been undertaken here, for the work seems fine and interesting.'[31] The publishing programmes of these institutions addressed goals outside the traditional marketplace of print culture and sought to control aspects of the publication process, all the while relying on the practices (and practitioners) of print culture.

The founding of learned academies, private societies, universities or training institutes elsewhere during the eighteenth century was an important aspect of the Enlightenment's preoccupation with science, and often one of the most tangible steps taken by these institutions was to provide a venue for the dissemination of knowledge. The examples of the Royal Society and the Paris Academy proved instructive. By the end of the eighteenth century, the publication of societies' proceedings, transactions, or memoirs symbolized the open and public exchange of scientific information, while at the same time it served as a tangible accomplishment of these collective bodies. Meetings were not enough. A successful society needed to expand its audience to a readership and thus tap into a network of correspondents, officials, agronomists, physicians, and others who would appreciate and contribute to its programme of encouraging discoveries, inventions and improvements.[32]

Traces of the efforts of these societies and academies can be found in libraries with extensive runs of scientific periodicals, such as those of the Royal Society and the Paris Academy, or in distinguished collections in the history of science. Ideally, these runs reach back to the beginnings of scientific periodicals in the late seventeenth century, with these titles supplemented by the publications of their major imitators and those of minor, regional and local societies as well. Most sets of early Royal Society and Paris Academy publications are mixed –

that is, composed both of original volumes and of later, unrevised editions, also published during the eighteenth century. Mixed and partial sets, usually ending in the late eighteenth or early nineteenth century, occasionally emerge for sale in the antiquarian book market. So too does the odd eighteenth-century offprint or separately paginated extract, generally by an eminent author. The existence of such early offprints suggests a circulation of information outside the circle of subscribers. These offprints often bear inscriptions as well, marks of their authors' concern for the reception of their work, and as such are often highly prized by collectors.

Self-publishing

Indeed, instances of the author's direct involvement with his work *as printed* can engage collector, historian and librarian alike. We have noted that both corporate bodies and some individual scientific authors turned to self-publishing (and even printing) as a method of controlling the content, appearance or dissemination of their work. Though in many respects they turned away from the primary considerations of most printers and publishers, such as their concern for the financial bottom line, self-publishing authors became part of that typographic culture by virtue of their role in producing and distributing printed works. We have written elsewhere of the motives and methods by which scientific authors became publishers and printers.[33] A few examples here suggest their direct experiences with the capabilities, limitations and economics of the instrument of print, as well as their motives in attempting to exercise control over that instrument.

Federico Commandino's firsthand involvement with printing and publishing demonstrates that at least some authors were self-conscious in their concern for codification, and in their appreciation of printing as a tool for codification. The printing of definitive texts of the classics of Greek mathematical learning benefited from wealthy and obliging patrons; the combined talents of the humanist scholar and the mathematician; and cooperative, erudite, and imaginative printers. The salutary results of such publishing programmes are evident in Commandino's editions of Aristarchus and Archimedes, which paid tribute to his patron and proved the value of typography for the renaissance of exact science. Commandino's reconstruction of missing texts and substantive commentaries enhanced the critical analysis and translation.[34] For his edition of Euclid, Commandino followed Regiomontanus' lead in taking on the duties of publisher as well.[35] Such works contributed much to what Elizabeth Eisenstein sees as signal accomplishments of printing, namely, 'rationalizing, codifying, and cataloguing data'.[36]

Also inspired by Regiomontanus, Tycho Brahe utilized the printing press as one of many instruments – some old, some new – for fashioning a new astronomy. Just as the arsenal of astronomical instruments in his observatory complex at Hveen sustained his vigilant watch over the accuracy of data pro-

duced there, so would the press afford him a similar degree of control over the integrity of their presentation. Woodcuts of his astronomical instruments served as gifts to eminent visitors, ornamented the astronomical correspondence printed at Uraniborg, and were prominent in the lavish *Mechanica* of 1598. They appeared again in later, even posthumous, printed editions of Tycho's correspondence in 1601 and 1610. Mismatched colophons and title page imprints reflect the confusing history of the sheets printed by Tycho's press.[37]

Publication offered fame, recognition, and perhaps the benefits of patronage. Yet authors and publishers also struggled with negative consequences of open and reliable communication, which by breaking down walls of secrecy also compromised protected proprietary interests. Galileo, for example, developed a useful and potentially profitable mathematical instrument, hired a craftsman to produce copies, tutored students in its use, and supplied an instruction manual, all for a fee. The printed version of the manual, published in his own home, skimped on details and illustrations that might be too revealing. Yet, despite Galileo's vigorous action against competitors and plagiarists, versions of the manual appeared numerous times in print in the seventeenth century, fully equipped with engravings.[38] Agostino Ramelli also opted for self-publication to protect his innovations. His book on machines, like Galileo's manual, was printed on a press 'in the author's house', where he could conveniently supervise all operations and control the release of proprietary information.[39]

Indeed, close ties bound instrument-makers, mathematical practitioners and the typographic community. Instrument-makers, particularly in England, stocked their shelves with books or even supplemented their incomes by publishing. Surveyors and other mathematical practitioners, not unlike Galileo, established this tradition in the seventeenth century when they published manuals and primers useful to those who needed to use instruments.[40] In his long career William Leybourn, for example, proved to be one of the most prolific of the mathematical practitioners in this group, both as author and printer. Either alone or in partnership with his brother, William printed an average of ten books a year from 1651 to 1661. He also wrote books, many of which were printed by the Leybourns and published by the bookseller George Sawbridge. Joseph Moxon was the son of a printer and had been trained as a mapmaker and hydrographer in Holland. He supplied globes, maps and mathematical instruments to his customers (who included Robert Hooke and Samuel Pepys), often acting as his own publisher. In the annals of typographic culture, he is notable for his manual on printing, originally composed and published as part of a series of 'mechanick exercises' on various useful arts.[41]

In the eighteenth century, published journals and books figured prominently in the growing commerce in scientific ideas, artefacts and instruments. Academies – in line with their mission to promote scientific enquiry – exchanged publications, just as they sent each other boxes of seeds, shells and stuffed birds. Whether acting as individuals or gathered in academies or societies, scientific authors who sought to control the process and production of publication did so

with a variety of motives and objectives: secrecy or publicity; institutional prestige, individual vanity, or opposition to constituted authority; accuracy; or even crass profit. The volumes themselves likewise vary in the extent to which they bear their authors' 'imprint', both metaphorically and bibliographically.

Fixity/mutability

It is a commonplace in comparisons of manuscript and print culture to point to the errors introduced in each scribal copy of a text. By contrast, printing is seen by some historians as promising control of intellectual content, that is, of the text itself, in all copies. Eisenstein's analysis of print as an agent of change emphasizes the control afforded by technologies of print as proving particularly advantageous for intellectual pursuits like science, since it offered the possibility of preserving a given text intact in multiple copies. These copies would – it is assumed – be identical in content, without the accumulated and idiosyncratic scribal errors that plagued texts copied and recopied in the manuscript era. Thus fixity – ideally in accord with the author's wishes – and multiplicity were two sides of the same coin so far as printed books were concerned.

The character of the printed book of science as both fixed and multiple, however, was easily compromised in typographic practice. The mutability of such works, as well as the possibility of unique printed copies(!), can engage both historian and collector, informed by what we know of typographic practice in early modern science.

Accommodating new information

Fixity itself was challenged by new information and the growth of the scientific enterprise. By the beginning of the seventeenth century, the trickle of scientific news had grown to a flood, recording everything from new stars to exotic medicinal plants. For some authors, self-publication made possible prompt reporting of noteworthy astronomical events like the appearance of a comet or nova.[42] Or consider the situation of botanical writers faced with the problem of plenitude. Leonhart Fuchs' great herbal of 1542 listed roughly 500 plants, hardly more than the number known to the botanists of the ancient world. Just 80 years later, Caspar Bauhin faced the task of dealing with some 6000 known plants in his *Pinax*, a twelve-fold increase. By the end of the seventeenth century, John Ray assembled a catalogue of the plant kingdom enumerating close to 20,000 distinct types.[43]

The flow of new discoveries and observations posed a two-fold challenge for printed books: presenting timely accounts of recent discoveries, while at the same time assimilating and organizing a vast body of reports. The world beyond Europe stimulated book publishing, as explorers and naturalists travelling to the Americas, Asia and Africa provided fresh knowledge of a staggering volume of

flora and fauna. The first naturalist owing his literary reputation to the New World was the Spaniard Gonzalo Fernández de Oviedo y Valdés. He provided the first exact descriptions in print of rubber trees, tobacco, cinnamon and other useful plants, including the first detailed discussion of maize. The appendix added to the second edition of Oviedo's report, published in 1547, exemplifies a common mechanism used by printers to disseminate new information: adding short, up-to-date reports to published works with an established reputation.[44] The Flemish naturalist Carolus Clusius (L'Ecluse) often included reports from other naturalists in his own books. On many occasions Christopher Plantin, his publisher and countryman, inserted late-breaking news provided by Clusius. These reports were added hot from the press as dated appendices. Sometimes these important communications announced that a New World plant had at last flowered in Europe; Clusius justified last-minute additions (here speaking of an appendix to an appendix that had previously been declared finished) by noting that 'I happened to see certain plants that nobody has mentioned yet'.[45]

The importance of timely publication was not confined to the field of natural history. Galileo's letters on sunspots included as an appendix his predictions for the motions of the Medicean stars (Jupiter's satellites) for March–April 1613 – that is, just after the publication of the book.[46] Other authors, in the midst of a lively scientific controversy, insisted on last-minute additions to their publications, generally to the dismay of the printer. Robert Boyle, for example, submitted a 'Hydrostatical letter' and reports of new experiments 'occasion'd by some [recent] objections of Dr. Henry More' for late inclusion in his *Tracts ... containing new experiments*.[47] Occasionally, such last-minute additions and changes resulted in differences between the issues of a printed work within a single print-run, a bibliographic matter of significance both for the researcher and the collector.

Realities of typographic practice also compromised fixity, and in the process compromised fidelity to the original. Printers could, for example, ill afford to keep standing type in anticipation of reprinting a work, nor could they necessarily afford new illustrations should a new edition be called for. Just as they had to return metal type to the case for new projects, they were likely to recycle illustrations, especially expensive ones, preserved in the form of woodcuts or copperplate engravings. One set of woodblocks, for example, was used for some two hundred years, from their preparation for the edition of Pietro Mattioli's commentary on Dioscorides published at Prague in 1565, through many more editions of Mattioli's book printed by Valgrisi at Venice, and ultimately their acquisition by Henri Louis Duhamel du Monceau, whose printers used them for the *Traité des arbres* of 1755. Despite their fragility, the woodblocks saw use again in a late twentieth-century publishing project, and the blocks themselves were then offered for sale. Several libraries rose to the bait, making individual blocks available for research use.[48]

Careful bibliographic investigations, in conjunctions with archival resources, have shown that a half-dozen or so sets of woodcuts supplied most herbals

published through the early seventeenth century. Standard illustrations met up with different texts in an odd mix of fixity and mutability. For example, recycled illustrations of corn and tobacco originally provided by Plantin for his authors – notably Clusius, Rembert Dodoens, and Matthias de l'Obel – would turn up later in the famous herbal of John Gerarde and in Hernández' *Nova plantarum*.[49] The herbal of Matthias de L'Obel first appeared in 1581; in the edition of 1591, Plantin combined illustrations from works by L'Obel, L'Ecluse, and Rembert Dodoens.[50] The last Plantin-Moretus edition of Dodoens' herbal of 1583 featured nearly 1500 illustrations and additions by Joost van Ravelinghen.[51]

The very malleability of the printed book, whether of astronomy or natural history, could therefore compromise the integrity of text and illustration and the intent of its author. Just a year after the initial Latin edition of Fuchs' herbal, he produced an expanded German edition, issued by the same publisher and featuring the same careful woodcuts. Like the Latin, the vernacular work was clearly popular and publishers elsewhere, largely unrestrained by the privilege system, hastened to oblige a growing audience. As noted above, the process of artistic and typographical compromise again involved new woodcuts copied and resized for smaller formats, and printers of later editions crammed poor copies of the illustrations onto smaller pages or dispensed with them altogether.[52]

Printers and publishers often had good economic reasons for rushing proofreading, resetting type, altering the size of pictorial information, and making changes that suited books to specific markets.[53] Bibliographers labour to untangle the results, their work made more difficult in cases where the task of editing collections of manuscripts or previously printed texts fell to several hands working independently. Consider Edward Topsell's two-volume *History of four-footed beasts and serpents*, assembled from contributions printed at various times and places. The preface to the second volume (that on serpents) readily admitted to 'manifold escapes in the Presse, which turned and sometimes overturned the sense in many places'.[54] When Conrad Gesner was editing an herbal by Valerius Cordus, Wendel Rihel encouraged him to select woodcuts to add to the book, probably with an eye to increased sales. Most of the woodcuts came from an earlier edition of another herbal by Hieronymus Bock. Gesner, or perhaps Rihel, matched them carelessly to Cordus' plants: one woodcut stood twice for two different plants, an unintended example of fixity.[55]

Unique and multiple

In tracing the results of fixity and mutability, it is important not to overestimate the extent to which identical copies produced by printing are in fact identical.[56] Bibliographers well know the variety of printed approximations to the 'ideal copy'. Collectors often prize the variants. But the problem of the unique and the multiple can and should engage the historian as well. All need to be guided by what we know of the making and marketing of printed books.

The work of Peter Apian, astronomer and printer, provides a telling, if unusual, example. Apian's printed masterwork, the *Astronomicum Caesareum*, featured multiple superimposed volvelles cut out to reveal layers beneath, as well as elaborate ornamentation hearkening back to illuminated manuscripts. Although most hand-coloured books of the period, and most with volvelles, were painted and/or assembled after purchase, just as it was the book buyer's responsibility to arrange for the binding of his purchase, the illustrations in the *Astronomicum Caesareum* were individually painted and the volvelles assembled in Apian's own workshop. Though the primary copies of the work were destined for the dedicatees, Emperor Charles V and his brother Ferdinand, the print run was considerably larger than two, despite the amount of individuation and investment in ornamentation and assembly.[57]

Colour often proved the crucial difference between a standard printed work and a unique 'copy', especially before the nineteenth century. Most early printed books, as products of the 'Black Art', lacked the rich information of colour. Colour, if it appeared at all, came from a paintbrush, a pen, a stencil, or from a separate inking or press run; and whatever the means of application, use of colour was patterned on manuscript models. A printed title inked separately in red called attention to the importance (or cost) of the book and required special typographic effort, but was common to multiple copies. Rubrics added by hand in red, following manuscript tradition, signalled logical divisions in the text; likewise, column and margin lines could be ruled in red. Elaborate initials or borders could be either printed from woodcuts and then hand-coloured or improvised in blank spaces left by the printer. As in illuminated manuscripts, such flourishes could make a copy of a printed work special – if not unique – indeed.[58]

Colour can carry information as well as ornamental value;[59] and, like manuscripts before them, a few early printed books used colour to enhance their intellectual content. This was, however, an uncommon representational strategy. If actual colour proved essential for a particular illustration, early typographic culture certainly offered the traditional possibility of hand-colouring commissioned by the purchaser. This practice of hand-colouring for scientific illustration persisted well into the 19th century and beyond.[60] If not only hand-colouring, but in fact consistent colour, was desired – as in a scientific treatment of colour theory – several options were possible. Inking the woodcuts separately or stencilling the whole press run meant the application of consistent colour before the copies left the shop. Authors and publishers to whom full control of the product was important might spring for in-shop colouring of all or some copies. Fuchs evidently supervised the colouring of at least some copies of his herbal; Goethe insisted on doing so for his treatise on colour.[61] Alternatively, a guide to the application of appropriate colours (paint-by-the-numbers) might be supplied to the purchaser of each copy. Whether the results of do-it-yourself colouring agreed with the author's intention is another matter: consider, for example, a botanical illustration coloured by someone who had never seen the plant in question.

Mixing manuscript and print

Mixing of manuscript and print – combining the resolutely unique and the mechanical multiple – was also common in early printed books of science, at least as they have come down to us. We must, however, distinguish between annotations by the book's author or printer and those by its readers or owners. We have already noted William Gilbert's attempt to correct errors by hand in printed sheets of his own treatise. Such annotations, true to the intent of the author or otherwise, might have also come from a reader's pen. We know too that many readers have added manuscript questions, comments and highlights to their books, and some of these can hold great interest for collector and scholar alike.[62] In other cases, intrusive marking can diminish monetary value and even impede readability. The choice of binding for a printed book might take consideration of the practice of manuscript annotation; a copy of *De morborum internorum curatione libri quatuor* owned by Johannes Eusebius included many bound-in sheets of manuscript notes, signed and dated 1564 by Eusebius.[63]

Manuscript annotation, like many other practices that originated in the scriptorial era, also found expression in print per se, in typographical versions of marginal glosses, pointing fingers, and commentaries surrounding basic text. In such instances, printing produced fixed and multiple copies of what had previously been highly personal objects mixing standard text and unique annotations. Perhaps in this sense of movement away from individually produced forms, the advent of printing increased the distance between the reader or buyer of a text and the text itself, because the technologies used to produce a printed book henceforth lay beyond the average reader's competence or experience. This had consequences, if subtle ones, for a sense of inviolability (or fixity) of the text as printed, whatever its perceived truth or utility. As the multiple character of the printed book may have prompted readers to make their copies unique by commissioning ornamental additions, it may also have prompted the owner of a book to make individual copies his/her own by marks of ownership, or by mastering the text with pen in hand.

We have concentrated on characteristics of the early modern scientific book, that is, the scientific book as printed before 1800. Significant changes in papermaking and printing technology early in the nineteenth century combined with changes in institutional and publishing practices in science to produce a markedly different, and larger, body of scientific literature. By way of epilogue, however, we want to stress the importance for librarians, collectors and historians of this expansion of scientific literature in the nineteenth and twentieth centuries. That expansion presents both challenges and opportunities. Considerations of space, fragility, price, bibliographic control and specialization, not to mention sheer numbers, figure among the challenges felt keenly by librarians in

both circulating libraries and rare book collections; they also affect collectors and dealers interested in modern science. Librarians now experience pressure to shift into higher-security areas 'medium-rare' scientific books and journals, especially those with attractive plates. Electronic 'aggregators' are eager to exploit on-line catalogues and digitizing technologies, and propose to produce comprehensive digital 'archives' of non-current scientific publications. As a result, some librarians face pressures to discard scientific collections deemed out-of-date in favour of surrogate, searchable, compact formats. But with these challenges come opportunities for new collections and new scholarship.

New historical studies of scientific practice, the 'new cultural history', growth of the field called 'history of the book', and computer-based library and information technology have all provided valuable new tools and insights to those concerned with the scientific book, early modern or otherwise. Rather than pointing away from the printed scientific book, research stimulated by these new inputs depends as much as ever, if not more, on library collections of breadth and depth that push beyond 'high spots' and static canons. Interdisciplinary research and the ready availability of powerful tools for retrieving and manipulating bibliographic information increase demand for collections that stretch intellectual boundaries and library confines. Indeed, the history of the system that creates and distributes scientific publications is just such an area of research, one which is creating opportunities for scholarship linking historians of science, library curators, book collectors, and historians of the book. Surely, the results of this work will be more than worth the challenges of building library collections to support it.

Notes

1. Eisenstein, Elizabeth (1979), *The Printing Press as an Agent of Change: Communications and Cultural Transformations in Early Modern Europe*, Cambridge and New York: Cambridge University Press, p. 53.
2. Ibid., p. 686.
3. See, for example, chapter VI, 'Ditto', in Schwartz, Hillel (1996), *The Culture of the Copy. Striking Likenesses, Unreasonable Facsimiles*, New York: Zone Books.
4. Some examples, most advertising the enlargement in their inflated titles: 'sGravesande, Willem Jacob (1747), *Mathematical elements of natural philosophy confirm'd by experiments: or, An introduction to Sir Isaac Newton's philosophy. The sixth edition greatly improved by the Author, and illustrated with 127 copper plates all new engraven*, London: printed for W. Innys, T. Longman and T. Shewell [etc.]: Cooke, James (1676), *Mellificium chirurgiae: or, The marrow of chirurgery much enlarged. To which is now added anatomy, illustrated with twelve brass cuts, and also The marrow of physick: both in the newest way*, London: printed by J.D. for Benj. Shirley: Culpeper, Nicholas (1659), *Pharmacopoeia Londinensis; or, The London dispensatory further adorned by the studies and collections of the fellows, now living of said colledg. In this sixt ed. you may find, 1. Three hundred useful additions ... 3. On the top of the pages of this impression is printed, The sixt edition, much enlarged ...*, 6th edn, London: printed by P. Cole, and his *The*

English physitian enlarged; with three hundred, sixty and nine medicines, made of English herbs that were not in any impression until this ... , London: George Sawbridge, 1681. *The first and seconde partes of the herbal of William Turner ... lately oversene, corrected and enlarged with the thirde parte, lately gathered, and nowe set oute with the names of the herbes in Greke, Latin, English, Duche, Frenche, and in the Apothecaries and herbaries Latin ...* , 4 vols in 1, Collen: imprinted by Birckman, 1568. De Fourcroy, Antoine-François (1788), *Elements of natural history, and of chemistry: being the second edition of the elementary lectures on those sciences, first published in 1782, and now greatly enlarged and improved by the author, M. de Fourcroy ... with occasional notes, and an historical preface, by the translator*, London: printed for G.G.J. and J. Robinson.

5. As described by Chartier, Roger (1994), *The Order of Books: Readers, Authors and Libraries in Europe between the Fourteenth and Eighteenth Centuries*, trans. Lydia G. Cochrane, Cambridge: Polity Press, p. 168.
6. For the literary realm of the nineteenth century, for example, see Rose, Jonathan, 'How historians study reader response; or, What did Jo think of *Bleak House*?' in Jordan, John O., and Patten, Robert L. (1995) (eds), *Literature in the Marketplace: Nineteenth-century British Publishing and Reading Practices*, Cambridge and New York: Cambridge University Press, pp. 195–212.
7. For recent discussions of de-accessioning in special collections libraries, see the articles by Oram, Richard W., Streit, Samuel and Szewczyk, David (1997), *Rare Book and Manuscript Librarianship*, 12 (1).
8. Lowry, Martin (1979), *The World of Aldus Manutius: Business and Scholarship in Renaissance Venice*, Ithaca: Cornell University Press, p. 227. Lowry cites the example of Marsilio Ficino in his relationship with Manutius. Concerning questions of control of the early modern book, the recent work of Adrian Johns came too late to be reflected here. Johns, Adrian (1998), *The Nature of the Book: Print and Knowledge in the Making*, Chicago: The University of Chicago Press.
9. Belon, Pierre (1553), *Les observations de plusieurs singularitez et choses memorables, trouvées en Grece, Asie, Iudée, Egypte, Arabie, & autres pays estranges, redigées en trois livres ...* , Paris: Gilles Corrozet, Gg3, recto-verso.
10. See the exceptionally revealing royal privilege printed in Rondelet, Guillaume (1554–55), *Libri de piscibus marinis, in quibus verae piscium effigies expressae sunt*, Lyons [Lugduni]: Matthias Bonhomme. a1, recto, 'Privilege du Roy'. On early printing privileges, see Hirsch, Rudolf (1967) *Printing, Selling and Reading, 1450–1550*, Wiesbaden: Otto Harrassowitz, 9, 81–87.
11. So, in fact, did publishers. Witness Aldo Manuzio's experience with pirated editions, as described by Lowry in *The World of Aldus Manutius*, esp. pp. 154–58. About Galileo's efforts to protect his interests in the military compass, see, for example, Stillman Drake's (1978) introduction to Galileo Galilei, *Operations of the Geometric and Military Compass, 1606*, trans. Stillman Drake, Washington: Smithsonian Institution Press, Dibner Library, no. 1.
12. An example of the carryover of images from medieval sources is to be found in the *Herbarius Patavie*, Passau: J.C. Petri, 1485.
13. Such was the case at least in the original printed editions they produced. Lowry discusses this topic in the chapter on 'Authorship and Editorship' in *The World of Aldus Manutius*, pp. 217–56.
14. On humanist programs to restore mathematical learning, see, for example, Rose, Paul Lawrence (1975), *The Italian renaissance of mathematics. Studies on Humanists and Mathematicians from Petrarch to Galileo*, Geneva: Librairie Droz, Travaux d'humanisme et renaissance, no. 145.
15. On the last point, especially, see Kernan, Alvin (1987), *Printing Technology, Letters, & Samuel Johnson*, Princeton: Princeton University Press. Cf. Rose, Mark

(1993), *Authors and Owners: The Invention of Copyright*, Cambridge, Mass.: Harvard University Press.
16. Harvey, William (1653), *The Anatomical Exercises of Dr. William Harvey ... Concerning the Motion of the Heart and Blood*, London: printed by Francis Leach, for Richard Lowndes, pp. **2v–**3r.
17. Weil, E. (1994), 'William Fitzer, the Publisher of Harvey's *De Motu Cordis*, 1628', *The Library*, 4th series, 24, p. 145; Keynes, Geoffrey (1989), *A Bibliography of the Writings of William Harvey, 1578–1657*, 3rd edn, rev. by Whitteridge, Gweneth and English, Christine, Winchester: St. Paul's Bibliographies.
18. Zachariah Wood (Sylvius), 'The Preface of Zacharie Wood ... upon the Anatomical Exercise of Doctor William Harvey', in *Anatomical Exercises*, pp. *8v–**1r; also *8r.
19. Emphasized by Elizabeth Eisenstein, and Walter Ong, respectively. Eisenstein, *The Printing Press as an Agent of Change*; Ong, Walter (1991), *Orality and Literacy: The Technologizing of the Word*, London and New York: Routledge, p. 81.
20. Marcia Goodman, librarian emerita of the History of Science Collection, University of Oklahoma Library (Norman, Oklahoma), has undertaken a census of copies of *De magnete* and their patterns of manuscript corrections. The copy at Norman of the first printed English translation of Euclid's *Elements* also contains a typeset correction, pasted onto the outer margin of *iiij (part of John Dee's mathematical preface), in type that strongly resembles the type used in a marginal gloss elsewhere in the volume. Not all copies carry this correction, but it is at least possible that Dee insisted upon its insertion in some copies.
21. From the dedicatory letter by Bock, dated 4 Feb. 1551, *Kreütterbuch* ... (Strassburg: Rihel, 1577), here cited from the reprint edn (Munich: Kölbl, 1964): b5, r–v. The praise for Egenolph must be seen in the light of earlier criticism aimed at the printer by Leonhart Fuchs; cf. Egenolph's *Adversum illiberales Leonhartii Fuchsii medici Tubingensis calumnias responsio* (Frankfurt: Ex officina nostra [Egenolph], 1544).
22. Greene, Edward Lee (1983), *Landmarks of Botanical History*, Stanford: Stanford University Press, vol. 1, p. 275. Leonhart Fuchs, *De historia stirpium commentarii insignes ...*, Basel: Michael Isingrin, 1542; *New kreuterbuch ...*, Basel: Isingrin, 1543; *Primi de stirpium historia commentariorum tomi viua imagines, in exiguam angustioremq; formam contracta ...*, also issued as *Labliche Abbildung und Contrafaytung aller Kreuter*, Basel: Isingrin, 1545 and 1549; *De historia stirpium commentarii insignes*, Paris: Apud Audoenum Parvum, 1546; *De historia stirpium commentarii insignes*, Paris: Apud C. Guillard, 1547; *De historia stirpium commentarii insignes*, Lyons: Apud Gulielmum Gazellum, 1547; *L'histoire des plantes mis en commentaries*, Lyons: Balthazare Anoullet, 1550; *De historia stirpium commentarii insignes*, Lyons: Balthazar Arnoullet, 1551; *De historia stirpivm commentarii insignes*. Lyons: apud Ioan. Tornaesivm et Gvl. Gazeivm, 1555; *Historia de yervas, y plantas*, Anvers: Por los herederos de Arnaldo Byrcman, 1557; *L'histoire des plantes mis en commentaires*, Lyons: Thibault Payan, 1558.
23. Lowood, Henry E. and Rider, Robin E. (1994), 'Literary technology and typographic culture: the instrument of print in early modern science', *Perspectives on Science 2* , pp. 1–37, esp. pp. 4–15.
24. See Gassendi's praise for Hevelius' abilities in this regard, as quoted in *Johannes Hevelius and his Catalog of Stars. The Millionth-volume Acquisition. The J. Reuben Clark, Jr. Library*, Provo: Brigham Young University Press, 1971, p. 15.
25. Birch, Thomas (1756–57), *History of the Royal Society of London for Improving of Natural Knowledge, from Its First Rise*, London: A. Millar, vol. I, p. 95.
26. Grew, Nehemiah (1681), *Musaeum regalis societatis; or, A catalogue & description of the natural and artificial rarities belonging to the Royal society and preserved at*

Gresham colledge, London: printed by W. Rawlins, for the author. The prefatory matter included notices that: 'At a Meeting of the Council of the Royal Society, July 18th 1678. Ordered, That Dr. Grew be desired, at his leasure, to Make a Catalogue and Description of the Rarities belonging to this Society. Thom. Henshaw Vice-Praeses R.S.' and 'At a meeting ... July 5th 1679. Ordered, That a Book entitled, Musaeum Regalis Societatis, &c. By Dr. Nehemiah Grew, be Printed. Thom. Henshaw, Vice-Praeses R.S.', [a6]v.

27. Rostenberg, Leona (1965), 'The New Science: John Martyn, "Printer to the Royal Society"', in: *Literary, Political, Religious & Legal Publishing, Printing & Bookselling in England, 1551–1700: Twelve Studies*. New York: Franklin, pp. 237–80, esp. p. 248.
28. *Philosophical Collections*, London: printed for J. Martyn, 1679–82, no. 1 (1679)–no. 7 (Apr. 1682).
29. See Hunter, Michael (1989), *Establishing the New Science: The Experience of the Early Royal Society*, Woodbridge, Suffolk; Wolfeboro, New Hampshire, USA: Boydell Press, p. 198 and Atkinson, Dwight (1999), *Scientific Discourse in Sociohistorical Context: The Philosophical Transactions of the Royal Society of London, 1675–1975*, London; Mahwah, New Jersey, USA: Lawrence Erlbaum Associates, chapter 2.
30. On the 'abandonment of anonymous publication by the academy', Hahn, Roger (1971), *The Anatomy of a Scientific Institution: The Paris Academy of Sciences, 1666–1803*, Berkeley: University of California Press, pp. 24 et seq.; for the *reglement* of 1699, Aucoc, *Lois*, p. lxxxix, quoted in translation in ibid., pp. 28–29.
31. Malpighi, Marcello (1669), *Dissertatio epistolica de bombycedos impressiones meteorologiques que se vieron el ano ...*, London: Apud Joannem Martyn & Jacobum Allestry, 1669. Letter of 16 June 1669 from Christian Huygens to Henry Oldenburg in: Oldenburg, Henry, *Correspondence*, Madison: University of Wisconsin Press, 1965–1986: vol. 6, 46.
32. McClellan III, James E. (1985), *Science Reorganized: Scientific Societies in the Eighteenth Century*, New York: Columbia University Press; Heilbron, J.L. (1983), *Physics at the Royal Society during Newton's Presidency*, Los Angeles, Calif.: William Andrews Clark Memorial Library; Lowood, Henry E. (1991), *Patriotism, Profit and the Promotion of Science in the German Enlightenment: The Economic and Scientific Societies, 1760–1815*, New York: Garland Publishers.
33. Lowood and Rider, 'Literary technology and typographic culture'.
34. Aristarchus of Samos (1572), *De magnitvdinibvs, et distantiis solis, et lvnae, liber; cvm Pappi Alexandrini explicationibus quibusdam. A'Federico Commandino Vrbinate in latinum conuersus, ac commentaries illustratus*, Pisa: [Apud] Camillum Francischinum.
35. Rose, Paul Lawrence (1975), *The Italian Renaissance of Mathematics: Studies on Humanists and Mathematicians from Petrarch to Galileo*, Geneva: Droz.
36. Eisenstein, Elizabeth L. (1979), *The Printing Press as an Agent of Change: Communications and Cultural Transformations in Early Modern Europe*, 2 vols in 1, Cambridge: Cambridge University Press, paperback 1980, reprinted 1982, 1985, p. 88.
37. Brahe, Tycho (1598), *Astronomiae instauratae mechanica*, Wandsbeck; *Epistolarum astronomicarum libri: quorum primus hic illustriss. et laudatis. principis Gulielmi Hassiae*, Nuremberg: [Apud] Levinum Hulsium, 1601. Cf. Lowood and Rider, 'Literary technology and typographic culture'.
38. E.g., Galileo Galilei (1656), *Le operazioni del compasso geometrico, et militare*, Bologna: H.H. del Dozza; see also Galileo (1607), *Difesa di Galileo Galileo control alle calunnie & imposture di Baldessar Capra ...* Venice: Tomaso Baglioni.
39. Ramelli, Agostino (1588), *Le diverse et artificiose machine*, Paris: In casa del'autore.

40. Taylor, E.G.R. (1954), *The Mathematical Practitioners of Tudor & Stuart England*, Cambridge [U.K.]: for the Institute of Navigation at the University Press. Cf. Taylor (1966), *The Mathematical Practitioners of Hanoverian England, 1714–1840*, London: Cambridge U.P. for the Institute of Navigation.
41. Reprinted as Moxon, Joseph (1958), *Mechanick Exercises on the Whole Art of Printing, 1683–4*, ed. Davis, Herbert and Carter, Harry, Oxford University Press.
42. Brahe, Tycho, *Epistolarum astronomicarum libri*, op. cit., and his *De nova et nvllivs aevi memoria privs visa stella iam pridem anno a nato Christo 1572, mense Nouembriprimum conspecta*, Copenhagen: Impressit Lavrentivs Benedicti, 1573. Also Hevelius, Johannes (1668), *Cometographia totam naturam cometarum ... exhibens*, Gdansk: Auctoris typis, & sumptibus, imprimebat Simon Reiniger.
43. Cf. Broberg, Gunnar (1990), 'The broken circle', in *The Quantifying Spirit in the 18th Century*, ed. Tore Frängsmyr, J.L. Heilbron, and Robin E. Rider, Berkeley: University of California Press, pp. 45–71.
44. Gonzalo Fernández de Oviedo y Valdés [1547], *Cronica de la Indias: la hystoria general de las Indias* ..., Salamanca: En casa de Juan de Junta ...
45. Clusius, Carolus (1605), *Exoticorum libri decem*, Antwerp: Ex officina Plantiana Raphelengii, ***1r.
46. Compare, for example, Stillman Drake's account in *Galileo at Work. His Scientific Biography*, New York: Dover Publications, 1978; reprint of 1955 edition, pp. 205–9, and the discussion of pressure to publish in Biagioli, Mario (1993), *Galileo, Courtier. The Practice of Science in the Culture of Absolutism*, Chicago and London: University of Chicago Press, pp. 65–66.
47. Boyle, Robert (1672), *Tracts ... Containing new experiments*, London: printed for Richard Davis, ...
48. Mattioli, Pietro Andrea (1565), *Commentarii in libros sex Pedacii Dioscorides ... de materia medica*, Venice: Valgrisi; Duhamel du Monceau, Henri Louis (1755), *Traité des arbres et arbustes qui se cultivent en France en pleine terre*, Paris: H.L. Guerin & L.F. Delatour. On the recent sale of the woodblocks, see *The Mattioli Woodblocks*, London: Hazlitt, Gooden & Fox, 1989 Fox, and Bernard Quaritch and Amsterdam: Junk. Stanford University Libraries own the pearwood block from this set labelled as depicting the plant Pimpinella major.
49. Hernández, Francisco (1651), *Nova plantarvm, animalvm et mineralivm Mexicanorvm historia*, Rome: Sumptibus B. Deuersini & Z. Masotti, typis V. Mascardi.
50. l'Obel, Matthias de (1591), *Icones stirpium, seu plantarum tam exoticarum, quam indigenarum*, Antwerp: Ex officina plantiniana.
51. See Lowood, Henry (1995), 'The New World and the European catalog of nature', *America in European Consciousness, 1493–1750*, ed. Karen Ordahl Kupperrnan, Chapel Hill and London: published for the Institute of Early American History and Culture by the University of North Carolina Press, pp. 295–323.
52. Lowood, 'The New World and the European catalog of nature', p. 307.
53. On the margins of scientific works compare, for example, the texts and illustrations of Thomas Hill's *A pleasant history: Declaring the whole art of physiognomy* ..., [London]: W. Jaggard, 1613, and his *A contemplation of mankinde; contayning a large discourse of all the members and partes after phisiognomie* ..., London: William Seres, 1571.
54. Topsell, Edward (1608), *The historie of serpents. Or, The second booke of liuing creatures* [etc.], London: printed by William Jaggard, 'To the Reader', A5v, about *The historie of fovre-footed beastes*; also in Topsell (1658), *The historie of serpents*, London: printed by E. Cotes, EEE1.
55. Cordus, Valerius (1561), *Annotationes in Pedacij Dioscorides De medica materia libros V*, Argentorati: excvd. J. Rihelius. On the problems with the illustrations in

this edition, see Greene, *Landmarks of Botanical History,* vol. I, pp. 372–73. Cf. Eisenstein, *The Printing Press as an Agent of Change*, 84–86, on the typical and the unique.

56. For an imaginative recent discussion, see Schwartz, *The Culture of the Copy. Striking Likenesses, Unreasonable Facsimiles*, esp. chapter 6.
57. See Gingerich, Owen (1989), 'Early astronomical books with moving parts', *AB Bookman*, 23 October, pp. 1505–8, esp. 1508. Cf. Rider, Robin E. (1993), 'Early modern mathematics in print', in *Non-verbal Communication in Science prior to 1900*, ed. Renato, Mazzolini (1993), Florence: Olschki, pp. 91–113. Gingerich has also noted the difficulty of assembling the volvelles properly, this with regard to a recent facsimile: Apian, Peter (1967), *Astronomicum Caesareum*, facsimile, Leipzig: Edition Leipzig. Cf. Wattenberg, Diedrich (1967), *Peter Apianus und sein Astronomicum Caesareum. Peter Apianus and his Astronomicum Caesareum*, trans. G. Archenhold, [Leipzig]: Edition Leipzig.
58. For a reprint of an early printed manual on illumination, see Boltz, Valentin (1976, 1988), *Illuminierbuch: wie man allerlei Farben bereiten, mischen und auftragen soll: allenjungen angehenden Malern und Illuministen nützlich undfürderlich*, Vaduz, Liechtenstein: Sändig Reprint, reprinting an edition of 1913 edited from the 1549 edn published by J. Kündig, Basel.
59. Notable examples are Euclid (1847), *The first six books of the Elements of Euclid in which coloured diagrams and symbols are used instead of letters for the greater ease of learners*, ed. Byrne, Oliver, London: Wm. Pickering; and Edward L. Youman (1857), *Chemical Atlas; or the Chemistry of Familiar Objects*, New York: D. Appleton & Co. first edition 1854. At least some copies of Youmans' work have hand-colouring added as well.
60. For example, the engraved and hand-coloured bodies of insects as depicted in Denton, Sherman Foote (1900), *As Nature Shows Them; Moths and Butterflies of the United States, East of the Rocky Mountains*, 2 vols, Boston: B. Whidden, originally issued in sections. Cf. Kemp, Martin (1900), *The Science of Art: Optical Themes in Western Art from Brunelleschi to Seurat*, rev. edn, New Haven and London: Yale University Press; and Gaskell, Philip (1972), *A New Introduction to Bibliography*, New York: Oxford University Press, pp. 261–62, 266–73, for details on new technologies for colour-printing.
61. Goethe, Johann Wolfgang von (1810), *Zur Farbenlehre*, Tübingen: Cotta. However, the coloured experiment cards included with his *Beyträdge zur Optik* Weimar: Industrie-Comptoir, 1791–92, were produced by a kind of colour block printing. The latter was reissued in Hildesheim by G. Olms (1964). For a general introduction to the history of colour printing, see Gascoigne, Bamber (1997), *Milestones in Colour Printing, 1457–1859, with a Bibliography of Nelson Prints*, Cambridge and New York: Cambridge Univ. Press.
62. For example, Newton's many marginal notes on his reading put his publishing writings and manuscripts in broader context. See, for example, More, Henry (1681), *A plain and continued exposition of the several prophecies or divine visions of the prophet Daniel, which have or may concern the people of God, whether Jew or Christian; whereunto is annexed a threefold appendage, touching three main points, the first, relating to Daniel, the other two to the Apocalypse*, London: printed by M.F. for W. Kettilby: Newton's copy, now at the Bancroft Library, University of California, Berkeley, contains his substantive marginal notes.
63. Fontanon, Denys (1560), *De morborum internorum curatione libri quatuor*, London: Ioannem Frellonium, the copy in Special Collections, Stanford University Libraries, annotated by Johannes Eusebius.

Chapter Two

Ancient Science[1]

Liba Taub

The problem with 'science'

Defining the 'scientific' book is a problem faced by all of the authors of this volume. In part the problem is due to the changing understanding, by modern practitioners, historians and philosophers, of what constitutes science. But also, the term 'scientist' is modern;[2] arguably, there is no exact analogue in other periods to that professional label. Indeed, historians, philosophers, sociologists and others who study the scientific enterprise have been much occupied by issues of definition. Although such issues cannot be addressed here, they must be acknowledged. Nevertheless, there are a number of ancient authors and texts which few, if any, historians would question as being properly included in the study of the history of science.

What is labelled 'scientific' is often a matter of taste. There are those scholars, for example, who claim that the ideas of the Presocratic philosophers were not scientific, while there are numerous others who would counter that they represent the beginning of the scientific enterprise. Again, these positions cannot be argued here, but the reader should take note that ancient writings which may be considered to be 'scientific' may look very different from the modern conception of such a work. There are many texts which have a form which the modern reader would regard as usual for a scientific work, including treatises, textbooks and manuals, but other forms and genres were also the vehicles for scientific ideas. Poetry, including the physical poem of Empedocles and the *De rerum natura* of Lucretius, must be included, as must the dialogue form, exemplified by the writings of Plato; other forms include collections of 'questions' or 'problems', which were posed and answered (for example the pseudo-Aristotelian

Problems), and astronomical tables (including Claudius Ptolemy's *Handy Tables*).[3]

The status of various human activities as scientific, non-scientific or even pseudo-scientific is not always clear-cut. The ancient Greeks were themselves very interested in classifying human activities. There was no one term, either in Greek or in Latin, which carried the meaning of the modern word 'scientific'. While some have suggested that the Greek word *episteme* is equivalent to the Latin *scientia*, this is arguable; furthermore, neither the ancient Latin word *scientia* nor its nearest Greek equivalent, *episteme*, conveyed the same meanings as our modern word 'scientific'. I have chosen to include works by authors who sought to explain nature (*physis*) and the natural world, many of whom are usually considered to have been philosophers. I have also included mathematical writers,[4] since many in antiquity who thought about such matters considered mathematics, like philosophy, to be a branch of theoretical knowledge. However, readers should be aware that ancient understandings of what constitutes mathematics and philosophy do not map on to modern conceptions in a straightforward manner. Just as today there is no unanimity regarding what constitutes science and scientific practice, so in antiquity people were not unanimous about the categories in which they placed those pursuits which might today fall under the historian's rubric of 'scientific'.[5] As G.E.R. Lloyd has noted, 'a distinction between "philosophers" and "scientists" is in general hard to draw in Greco-Roman antiquity. Natural science is a domain that straddles both those disciplines as *we* perceive them.'[6]

Most of the work on ancient science outside of the Greco-Roman world has been due to the efforts of a very small group of scholars, who have largely devoted themselves to the study of mathematics and astronomy. As Francesca Rochberg noted in a recent issue of *Isis* focusing on ancient science, 'the field as a whole still has not taken full account of the ancient Near Eastern and South Asian sources now available, with the consequence that, by and large, works of "universal" history of science do not go beyond acknowledging a certain technical sophistication of ancient oriental science.' Within the same issue of *Isis*, David Pingree decried what he referred to as the 'Hellenophilia' of many historians of science, warning that the characteristics which define Greek science do not necessarily fit all scientific traditions.[7] The primary focus of this section on Greco-Roman science should be regarded as being due to the limits of my own expertise, and nothing more pernicious.[8]

What is a 'book'?

The answer to the question of what is a 'book' in antiquity is not straightforward. There is much primary material relevant to the history of science which is not now (and was not in antiquity) in 'book' form. There are also some texts which had a dual existence, for example letters which were circulated, preserved

and published in collections. I have not been exhaustive in my inclusion of manuscript, papyrus and cuneiform texts, but have attempted to give an indication of the wealth of material which is available and the resources through which such texts can be located. While the space here does not permit a comprehensive bibliography, I hope that the bibliographic aids provided will enable readers to address their own interests and needs.

As we shall see, few ancient texts would be recognizable to the modern eye as 'books'; furthermore, ancient texts were generally read aloud.[9] Perhaps more importantly, many ancient scientific texts have a radically different form from that of modern scientific texts. If we take the view that to be a book is to be a text which is published, that is made public, perhaps publicly displayed stone inscriptions might count as books, or at least, as publications.[10] Private communications, for example a letter sent from one person to another, would not (normally) be published documents or books. Taking the narrow view that a scientific work is a prose treatise or textbook would eliminate many important texts which are recognized as scientific, not only from the ancient but from later periods as well. Do we take the view that a book must have existed, at some point, in more than one copy? Mesopotamian astronomical texts produced for the royal court would not likely be regarded as books, although they are invaluable historical documents. However, the late second-millennium Mesopotamian MUL.APIN cuneiform compendium of a variety of astronomical texts perhaps should be regarded as a book, having clearly been copied numerous times.[11]

The shape of ancient 'books' would, no doubt, surprise the modern reader. It must first be emphasized that ancient authors would not recognize the form in which their writings are now available. Little of the physical evidence of ancient scientific books survive. Regarding books in general, evidence which survives for the archaic and classical periods is scant; most of our knowledge about the physical characteristics of ancient 'books' comes from Hellenistic material. (For our purposes, the death of Aristotle in 322 BC provides an appropriate date for the beginning of the Hellenistic period.)

The ancients used a wide variety of writing surfaces, including clay tablets, wood and animal skins, but by far the most widespread material used for writing was papyrus. The plant is native to Egypt and from perhaps 3000 BC the Egyptians manufactured papyrus sheets to be used for writing. The first-century AD Roman writer Pliny the Elder provided a description (in his *Natural History* 13.74–82) of their production. The sheets were pasted together to form rolls, which seem to have been the standard unit for manufacture and for sale of papyrus, although the widths of rolls varied, as did the length.[12] Because the rolls could not accommodate a large amount of text, in many cases a single work required several papyrus rolls. This is the origin of the division of ancient works into 'books'.

The papyrus roll was, for much of antiquity, the most common form of book and the standard medium for publication. In addition to written descriptions of

rolls, such as that contained in Pliny, ancient illustrations of rolls being used by readers exist, including vase paintings from fifth-century BC Athens.[13] Papyrus rolls, and fragments of rolls, have survived in scattered sites throughout the ancient world.[14]

Publication in the ancient world was, in contrast to much of modern practice before the Internet, extremely casual; no copyrights existed nor were royalties paid.[15] Very little is known about the actual production of texts on papyrus; for example, it is not known whether rolls were copied by dictation, by reading or both. L.D. Reynolds and N.G. Wilson have emphasized the difficulty of reading ancient texts, which contained rudimentary punctuation and no divisions between words. They suggest that 'a high proportion of the most serious corruptions in classical texts go back to this period and were already widely current in the books that eventually entered the library of the Museum at Alexandria.'[16]

Although the papyrus was the standard form for the publication of literary texts and philosophical treatises, other formats existed and were used, sometimes for specific purposes, such as letters. Between the end of the second and the fourth century AD, the papyrus roll was gradually displaced as the most usual form of book by the codex. The codex format utilized wax-coated wooden tablets and, eventually, parchment leaves. While the precise reasons for the adoption of the codex are not clear, in retrospect scholars have pointed to what may be regarded as advantages, arguing that the codex was less costly to produce, held more text, and was easier to handle than a roll. Athenian vase-paintings depict readers having trouble with a twisted roll; Pliny the Younger reports that the aged Verginius Rufus broke his hip while trying to recover a dropped roll.[17] C.H. Roberts and T.C. Skeat emphasized the role that the new Christian faith played in the adoption of the codex,[18] but the shift from the papyrus roll to the parchment codex was gradual, involving many innovations and changes in practice. Evidence suggests that Romans, rather than Greeks, first used parchment notebooks. Strikingly, only two Greek writers in the first two centuries AD mention the parchment notebook; one is the physician Galen, who describes a treatment for baldness recorded in a parchment notebook.[19] While the bulk of surviving ancient codices are devoted to Biblical and literary material, they also include astronomical tables, herbals, medical and magical prescriptions, as well as treatises on mathematics, Aristotelian physics, and astronomy.[20]

Many scholars have suggested that it was much easier to find a particular passage in a codex than in a papyrus. The physical difficulty of accessing text is very likely to have affected the ways in which ancient readers, commentators and editors worked. Some scholars have argued that the production of standard texts was made easier by the codex, claiming that it is 'much harder to make undetectable additions to or deletions from a codex; with a roll, sheets may be pasted in or removed at whim',[21] but this view is not universally accepted.

The earliest surviving texts

The oldest surviving Greek literary texts (likely dating from the eighth century BC), the epic Homeric and Hesiodic poems, provide our earliest information about the world of the ancient Greeks and offer a window on a pervasive ancient worldview. The Hesiodic *Works and Days*, a sort of farmer's almanac, contains astronomical lore for predicting the weather; this work may be related to the later *parapegmata*, which correlated astronomical phenomena with weather.[22]

The earliest figures associated with ancient Greek science, the sixth-century BC Ionian philosophers Thales of Miletus, Anaximander and Anaximenes, left no writings which survive. In fact, it is not clear whether Thales wrote anything at all.[23] What is known about their ideas has come through descriptions and quotations in works by later authors. The ancient scholarly tradition of discussing and commenting on the work of predecessors is responsible for what is known about many of the ancient philosophers and mathematicians. In many cases most, if not all, of the surviving information about particular authors and texts is to be found only in writings by a much later author. Further, we must also consider the survival and transmission of those texts into our own period. We are, in all cases, dependent on versions of the writings of ancient authors which have passed through several filters, or intermediaries, between the author and ourselves. In most cases, any given text will have passed through many hands before it finally reaches a modern reader; the texts will have been copied, translated and edited, and these activities may each have occurred in any or all of the relevant periods, ancient, medieval and modern. In this section, we will only be concerned with the fate of the texts in the ancient period.

The ideas of the Presocratic thinkers have been preserved and reported by writers from Plato (4th C. BC) to Simplicius (6th C. AD); in some rare cases, Byzantine authors have also preserved fragments. Modern scholars sometimes distinguish, not uncontroversially, between two forms of preserved texts: 'fragments' of writings quoted by later ancient authors and 'testimonies', or accounts of views, once again presented by other writers. While it might seem natural to assume that an older source would be more reliable, this is not always the case, for individual authors may not themselves have had access to reliable texts. Furthermore, individuals will not have been equally careful in copying texts, nor will they have been copying them for the same set of reasons, of which preservation may only be regarded as one possible motivation. Certainly, modern readers must be sensitive to the many possible motives present when one writer presents the views of another.

Doxography, historiography and reconstruction

Ancient authors who wrote on the doctrines, or *doxai* (opinions), of the philosophers are called doxographers. Many doxographies were compiled; only a few are

mentioned here. Aristotle may be regarded as an ancestor of the doxographers; he often prefaced the presentation of his own ideas with a synopsis of the views of his predecessors. His student Theophrastus dedicated an entire work, composed of 16 books, to an account of the ideas of Aristotle's predecessors, *Physical Doctrines*.[24] Working in the tradition of Theophrastus, but supplementing his summary from other Hellenistic authors, probably in the late first century AD, Aëtius compiled a summary of the ideas of the Greek philosophers; his work was an important source of information about philosophers whose writings have not survived, but his account has itself not survived in the original form. His text has been reconstructed by H. Diels from later doxographical summaries transmitted through the pseudo-Plutarchean *Epitome of Physical Opinions* and the *Physical Extracts* in Iohannes Stobaeus' *Anthologion* (*Eclogae*).[25]

One of the most important doxographers must be Diogenes Laertius (first half 3rd C. AD), simply because his work has survived. He provided biographies and summaries of the opinions of the ancient philosophers, beginning with Thales (6th C. BC) and ending with Epicurus (341–270 BC). Unfortunately, nothing is known about Diogenes Laertius himself. He compiled his own work by relying on and quoting from earlier (now largely lost) compilations. Thankfully, he often credits his sources, naming over 200 authors and over 300 works. The reliability of his work varies considerably, but it is, nevertheless, invaluable in many cases.[26] It should be emphasized that many other doxographical accounts were produced; limitations of space will allow the mention of only a few others as relevant.[27]

The motivations for compiling excerpts of various writers must have been numerous; scholars have pointed to the difficulty of handling the papyrus roll and of finding a particular passage as providing some motivation for the excerpting practice. The practice of excerpting interesting passages seems to have been an old one.[28] Evidence from Pliny the Younger (*Letters* Book 3.5), regarding the working habits of his uncle Pliny the Elder, indicates that excerpts were copied on to rolls. However, it has been noted by Jens Erik Skydsgaard that copying from one roll to another would not have solved the difficulties inherent in handling rolls and finding particular passages.[29] Whatever system of keeping track of the excerpts was employed is not known and the inherent difficulties of dealing with source material which has been excerpted, quoted, misquoted and paraphrased should be kept in mind.[30]

The ancient authors who wrote on the history of philosophy presented their material in various ways. For Aristotle, such histories were prefaces to his own ideas, but other authors chose to organize material in other ways, for example biographically, or by philosophical schools. Readers must be alert to the fact that excerptors selected passages for their own purposes, not for the sake of modern scholars. The authors of antiquity were writing for themselves and their audiences. The selection and presentation of the opinions of others was done deliberately, and is always subject to interpretation and misinterpretation, understanding, as well as misunderstanding, and, in some cases, deliberate distortion.

The Presocratics

The standard collection of fragments and 'testimonia' of the Presocratics, taken from a fairly wide variety of ancient sources, is H. Diels (1934–37), *Die Fragmente der Vorsokratiker*, 5th and later editions, Berlin, edited by W. Kranz.[31] A partial translation of many of the fragments can be found, together with commentary, in G.S. Kirk, J.E. Raven and M. Schofield (1983), *The Presocratic Philosophers*, 2nd edition, Cambridge: Cambridge University Press (often referred to as 'KRS'). In the original edition, Kirk and Raven explained that they limited their choices to the major Presocratic 'physicists' (*physikoi*) and their predecessors, focusing on figures whose main interest was in nature (*physis*).[32] (The collection is not meant to be a comprehensive corpus of texts relating to early science; unless it is related to the major Presocratics, work on mathematics, astronomy, geography, and medicine was not included.) There is a vast secondary literature on the Presocratic philosophers; the bibliography contained in KRS provides a good starting point.[33]

The variety of genres in which the Presocratics presented their ideas is striking. For example, Parmenides of Elea, Empedocles of Acragas and Xenophanes of Colophon chose poetry as the vehicle for their philosophy. In some cases our knowledge of the Presocratics includes titles of now-lost works. Although the content of these books does not survive, the lists are themselves of interest. To some extent, we must understand such lists to be somewhat traditional or clichéd, citing works it was assumed the author should have written. Further, the lists may only have been produced at a far remove from the subject's lifetime. So, for example, the tenth-century historical lexicon known as the *Suda* credits Anaximander with having written works entitled *On Nature*, *Circuit of the Earth*, *On the Fixed Stars* and the *Celestial Globe*.[34]

While such booklists must be treated with caution, the titles contained in such lists do give an indication of the sort of range of interests and activity which were deemed acceptable and worthy at the time of the compilation of the list. In any case, it is clear that many of the works of the earliest Greeks to write about nature are lost, their contribution having been absorbed and the original work made redundant. However, it should be emphasized that by no means are the works of the Presocratics the only ancient texts no longer extant; indeed, it appears that a vastly greater number of ancient scientific books, by a wide variety of authors, were lost than have survived.

Plato

In contrast to the fragmentary survival of the writings of his predecessors, it is generally believed that all of Plato's 'published' writings survive. Perhaps not surprisingly, given his place in the history of philosophy, more writings exist with an attribution to him than were likely written by Plato. The genuineness of

some of the dialogues, and many, if not all of the letters, has been questioned since antiquity. In addition to the *Apology*, there are 25 dialogues which are generally accepted as genuine, a number of others whose attribution is uncertain, several which are reckoned as spurious, and 13 letters which are attributed to Plato. Modern scholars have debated at what point Plato's works were collected and edited by his followers.[35]

The dialogue form of most of the Platonic writings is itself intriguing. Diogenes Laertius explained the dialogue form, noting that it is 'a discourse consisting of question and answer on some philosophical or political subject, with due regard to the characters of the persons introduced and the choice of diction'.[36] He added that various scholars had organized the dialogues into related groups, including Claudius Thrasyllus of Alexandria (d. AD 36), who also wrote on astrology, and who grouped Plato's dialogues into tetralogies, 'like those of the tragic poets'.[37] Diogenes Laertius also explained the various marks inserted by editors, and reports that 'Antigonus of Carystus says in his *Life of Zeno*, when the writings were first edited with critical marks, their possessors charged a certain fee to anyone who wished to consult them.'[38] Here, we get a sense of the scholarly enterprise which was involved in creating the ancient 'book'; to some extent such 'books' must be regarded as the products not only of the original authors, but of the scribes and editors as well. Scholarship involved collecting and ordering texts; individual writings were not studied in isolation but were considered as part of a larger body of work, and as part of a greater literary (and philosophical) tradition.[39]

It is interesting that while Plato chose the dialogue form for his publications, he never included himself as a speaker. While many have assumed that Socrates serves as Plato's mouthpiece, the extent to which this is the case is a matter of debate, and so it is not always clear which ideas espoused in the dialogues were actually held by Plato himself.[40] The speakers in Plato's dialogues discuss a wide variety of topics, many of which have special import to those concerned with scientific inquiry, and with the history and philosophy of science.[41] Issues relating to the nature of knowledge, the value of sense-perception, and the uses of language are particularly relevant. In Book 7 of the *Republic*, Glaucon and Socrates discuss those subjects which are preliminary to the study of dialectic; these include a range of mathematical topics, including astronomy.[42] Plato's interests were very broad, but the place of mathematics in the educational system he promoted has been a topic which many have found especially fascinating.[43]

Within the Platonic corpus, the *Timaeus* is unique, both in its content and its historical significance. Nominally a dialogue, the work is largely a monologue, in which Timaeus gives an account of the creation and structure of the universe. However, the idea that the universe was created was rejected by Plato's most illustrious student, Aristotle. While the *Timaeus* appealed to many readers, it should be noted that some of his own pupils did not think that Plato intended the dialogue to serve as a literal account of creation.[44]

While we are primarily concerned here with Plato's own writings, there are reports regarding his life and work, particularly his oral teaching, contained in the writings of Aristotle and others.[45] Some scholars stress the value in studying reports of Plato's teaching (his 'unwritten opinions'),[46] particularly because of the emphasis on the limitations of language present in his writings, and because he was never a speaker in his own dialogues.

Part of Plato's fame justifiably rests on his teaching and the subsequent contributions of his students. Around 385 BC, Plato founded a school known as the Academy in a park sacred to the hero Academus (Hecademus), in the outskirts of Athens. The Academy remained in continuous existence for many centuries, undergoing a series of reorientations under successive heads of the school.[47] Plato's immediate successor, his nephew Speusippus of Athens (c. 407–339 BC), wrote on ethics, as well as mathematics, and the problems of establishing definitions. This latter interest may have led Speusippus to work on his *Homoia (Similar Things)*, in which he collected observations about the resemblances between different plants and animals.[48] Xenocrates of Chalcedon was head of the Academy from 339–314 BC. According to Diogenes Laertius, he left a very large number of treatises and poems on a wide variety of topics, including ethics and mathematics. Diogenes Laertius also reports that when 'some one who had never learnt either music or geometry or astronomy, ... wished to attend his lectures, Xenocrates said, "Go your way, for you offer philosophy nothing to lay hold of."'[49] Occasionally, previously lost ancient works are rediscovered; such was the case with a fragment of Xenocrates.[50]

Aristotle

Perhaps surprisingly, even in the case of Aristotle, only a portion of his writings survive.[51] Once again, Diogenes Laertius (Book V 22–27) provided a list of Aristotle's writings, and commented on the large number of works included;[52] as is usual in the ancient booklists, some works attributed to the author are spurious.

Aristotle's writings have, since antiquity, been regarded as falling into two distinct groups: the exoteric works written for a wide audience and the more technical (known as the esoteric), and presumably less polished, writings intended for use by students and other philosophers. Nothing, except for a few fragments, survives of the exoteric works, whereas all that does survive would have been esoteric. Jonathan Barnes, editor of the revised version of the 'Oxford Translation' of Aristotle's writings and the *Cambridge Companion to Aristotle*, has explained that in the case of the Aristotle, 'when you pick up the *Metaphysics* or the *Nicomachean Ethics*, you are not picking up a finished philosophical text'. Rather, seeking to refute the generally held notion that what survives are lecture 'notes' or 'records', Barnes quite reasonably cautions against 'the perilous supposition that Aristotle taught and worked in much the same way as a

twentieth-century professor' and suggests that 'it is proper to assume that you are picking up a set of papers united by a later editor; and it is proper to assume that you are reading a compilation of Aristotle's working drafts'.[53]

Aristotle scholarship is a huge industry. An excellent, recent (and far more than introductory) bibliography is included in *The Cambridge Companion to Aristotle* (1995), compiled by Jonathan Barnes, Malcolm Schofield and Richard Sorabji.[54] Here, it will suffice to give an indication of the range of Aristotle's scientific interests. In many of his writings, and particularly in the *Posterior Analytics*, Aristotle addressed issues relating to the nature of knowledge (*episteme*); he was interested in defining the character of scientific explanation. In his work known as the *Physics*, Aristotle focused on dynamics and the explanation of change. His views on cosmology are primarily to be found in *On the Heavens*; the work known as *On the World* is spurious. Aristotle introduced the *Meteorology* by explaining that this work deals with 'everything which happens naturally' in that region which borders on the heavens, but with less regularity than what occurs in the heavens; comets, meteors and earthquakes are treated, as well as wind, rain and hail. In the fourth book of the *Meteorology*, Aristotle discussed the properties of a variety of natural substances; this book has been read by some as a work of chemistry.[55] Aristotle wrote a number of biological works, which together comprise more than one fifth of his extant writings and include *History of Animals*, *On the Parts of Animals*, *On the Generation of Animals*, *On the Motion of Animals* and *On the Progression of Animals*. The subject matter of the short treatises known collectively as the *Parva Naturalia* is the *psyche* or soul; the *Parva Naturalia* includes *Sense and Sensibilia*, *On Memory*, *On Sleep*, *On Dreams*, *On Divination in Sleep*, *On Length and Shortness of Life*, *On Youth, Old Age, Life and Death* and *Respiration*. Another, longer work, *On the Soul*, also survives.

For Aristotle, to study 'psychology' was to give an account of the characteristic activities of living beings. In the *Metaphysics* Aristotle discusses what he called primary philosophy (or theology), which deals with the first principles, or causes of things. The *Metaphysics*, which is like an editor's compilation rather than a unified treatise, comprises 14 books which range over a variety of topics, some of which are methodological; other subjects include the nature of substance, the unmoved mover (which may be regarded as the supreme entity in Aristotle's universe), and the philosophy of mathematics.

To some extent, Aristotle must be regarded as an 'accidental' historian of science. In his writings, Aristotle sometimes included information about his predecessors; his purpose, however, was not to provide a history of philosophy but rather to provide a backdrop for his own views. He provided few direct quotations but often gave a review of the work of earlier thinkers before presenting his own ideas. Although he tended to be critical of those who came before him, Aristotle does provide valuable, if not entirely objective, information about some of his predecessors and contemporaries.

Aristotle's school

Like Plato, Aristotle founded his own 'school', known as the Lyceum,[56] and his students followed him in compiling histories. Eudemus of Rhodes (later 4th C. BC) wrote on the history of arithmetic, geometry, astronomy and theology, as well as other topics. Some passages of his work on physics were preserved by Simplicius in the sixth century AD.[57]

Theophrastus, Aristotle's successor, wrote separate works on some of his predecessors, including Anaximenes, Empedocles, Anaxagoras, Archelaus and Democritus, but none of these survive. While most of his writings are lost, the *Characters* (describing various types of people), an essay on *Metaphysics* and two botanical works, the *History of Plants* and the *Causes of Plants* survive, along with short works including *On Winds*, *On Fire*, *On Stones* and *On Odours*; the attribution of *On weather-signs* is not certain. Recently, Theophrastus has been the long-overdue focus of scholarly attention.[58]

Libraries and scholarship

As Aristotle's successor, Theophrastus provided buildings for the school, which became known as the Peripatos, named after the *peripatos*, or covered walk. The geographical writer Strabo (64/3 BC–after AD 21; 13.1.54 (=13.608)) suggests that Aristotle was the first to gather books together into a library, reporting that he assembled a large collection of books.[59] While Diogenes Laertius (III 9) mentions that 'some authorities, among them Satyrus, say that [Plato] wrote to Dion in Sicily instructing him to purchase three Pythagorean books from Philolaus for 100 minae', Plato's collecting activity seems to have been on a much smaller scale than that of Aristotle. This fits in with other things we know about the two philosophers; Aristotle seems to have been genuinely interested in collecting as an activity.[60] B.M.W. Knox has argued that, ancient references to other collections of books notwithstanding, it is 'with the establishment of Aristotle's philosophical school, the Lyceum, [that] we come to the first serious institutional library, in the modern sense of the word – a tool for research; this is probably why Strabo (13.608) called Aristotle "the first whom we know of who collected books"'. Diogenes Laertius (IV 5) reported that, according to Favorinus, Aristotle purchased Speusippus' books for three talents, a large sum. Aristotle appears to have done much to inculcate the scholarly habit of excerpting from other authors. As Knox has noted: 'evidence of wide reading and frequent consultation of books meets us at every turn in his writings and in the work of his school.' Knox quotes Aristotle's admonition (*Topics* 105b) that 'we ought to make extracts also from written works'; Knox notes that Aristotle did so 'is clear from his constant citation from earlier writers: the more than thirty philosophers and poets cited in the *Metaphysics*', serves as an example. According to Knox, it is in Aristotle's *Rhetoric* (1407b) that 'for the

first time we are presented with critical remarks which refer specifically to the text visualized as a written page rather than conceived of as something heard; Aristotle evidences Heraclitus as an author "difficult to punctuate"'.[61]

Recent research has indicated the important and varied roles which oral literature, performance, oratory and transmission filled in ancient Greek and Roman society;[62] nevertheless, the rise of scholarly activities and the emphasis on written texts are an important characteristic of the Hellenistic age. Those scholarly activities developed, and relied upon, institutional support and the availability of texts to be studied. The physical institution of the Peripatetic school was assured through the will of Theophrastus and his successors. His immediate successor Strato bequeathed the school, along with the books and furniture, to his successor, and so on; Diogenes Laertius provides the texts of their wills, in which Theophrastus and Strato both explicitly mention the bequest of books.[63] Pfeiffer claimed that 'it is mainly due to these two firmly established Athenian organizations [the Academy and the Lyceum] that relatively many works of their founders are well preserved; they were better able to collect, copy, distribute, and hand them on to posterity than any previous philosophical circles in the east or west'.[64] Yet in spite of the institutional support, a great number of works, including many of Aristotle's own, were completely lost. Indeed, the history of Aristotle's library is by no means as straightforward as some of the ancient accounts suggest.[65]

Other important institutions devoted to scholarship were established during the Hellenistic period, most notably the Museum in Alexandria, which was founded by Ptolemy Philadelphus c. 280 BC. The Library formed an essential part of the institution. Apparently, in the previous reign the first Ptolemy had invited a pupil of Theophrastus, Demetrius of Phalerum, to set up a library, around 295 BC. Once established, the library quickly grew, although it is difficult to determine the number of volumes it actually contained.[66] The Alexandrian Museum was for a time unrivalled as a scholarly institution, but the persecution of scholars by Ptolemy Euergetes II (145 BC) resulted in an inevitable decline. Several generations of rulers at Pergamon supported work in philosophy and mathematics, inviting distinguished figures to their court and also establishing an important library.[67] The movement of scholars across the ancient world was important for the distribution of books, which scholars sometimes took with them.

R. Pfeiffer, in his *History of Classical Scholarship*, noted that it is to 'the later decades of the fourth century BC that we can assign the earliest of the papyri which have come to light in Egypt and provide us with actual specimens of Greek books'. He suggested that with the establishment of the Alexandrian Library, 'it is obvious that we have reached the age which we called – hesitatingly – a "bookish" one; the book is one of the characteristic signs of the new, the Hellenistic, world'.[68] But, as E.G. Turner has pointed out, once we start to talk about 'books' and 'editions' produced by scholars, we must be careful not to make anachronistic assumptions. The use of the word 'edition' did not imply

that multiple copies were available through a commercial publisher; rather, an 'edition' indicates that 'the work in question was available for consultation and presumably for copying, "published" in the sense that its existence was known and that it was "issued" to readers'.[69] In many cases, it is through the efforts of the ancient scholars, who produced abridgements, commentaries and compilations of other texts, that we have what survives of much of ancient learning, albeit often in fragmentary form.

However, the scholars and librarians were not merely conduits passing along the ideas and opinions of others. For example, Eratosthenes of Cyrene (c. 285–194 BC) succeeded Apollonius of Rhodes as head of the Alexandrian Library. Although none of his writings survive in their entirety, he wrote on a variety of subjects, including ancient comedy and chronology. He also produced works on geography, on a number of mathematical topics, including the duplication of the cube, and, perhaps most famously in modern times, *On the Measurement of the Earth*. Although he was a librarian, only fragments of Eratosthenes' own writings survive.[70]

Hellenistic philosophical writers

For the most part, scientific topics were not central in the work of Hellenistic and post-Hellenistic writers interested in philosophy; rather, their major interest was, for the most part, in ethics.[71] Nevertheless, many of these thinkers did devote some portion of their writings to scientific subjects, as well as to issues relating to methods, and the philosophy of science. However, even when considering scientific texts, it is useful to be mindful of the centrality of ethics to Hellenistic philosophy. Often the Hellenistic philosophers are described with reference to their 'school' affiliation, whether the Academy, Peripatos, Stoa, Garden of Epicurus, or some other school.[72] In many cases, the writings of individuals no longer survive and so ideas are often attributed not to individuals, but to 'schools'. As is so often the case with ancient writings, our knowledge of the contents is dependent on descriptions by other ancient writers.

According to Diogenes Laertius, Epicurus (341–270 BC) was an especially prolific author, who wrote about 300 rolls. Not surprisingly, most of this is now lost, but Diogenes Laertius, in his tenth book, preserves several texts, including letters and some forty moral maxims known as the 'Key Doctrines' (κύριαι δόξαι=*Ratae sententiae*). The *Letter to Herodotus* deals with physics, while the *Letter to Pythocles* discusses celestial phenomena; the *Letter to Menoeceus* summarizes Epicurus' views on ethics.[73] Epicurus' physical theory relied on the existence of atoms (indivisibles) to explain the natural world. His ideas were preserved and reached a wider audience through the poem *De rerum natura* written by Lucretius.[74] The Epicurean Philodemus (c. 110–c. 40/35 BC) also worked to popularize philosophy, writing a biographical history of Greek philosophy in ten or more books. Extensive papyrus remains of his work were found

carbonized and preserved at Herculaneum, including *On Signs*, an important text on scientific method.[75]

Even though the Stoics were particularly interested in a number of scientific subjects, including physics, astronomy and physiology, no books by Zeno of Citium (founder, died 262 BC), Cleanthes (head from 262 BC), Chrysippus (head from 232 BC), or Panaetius (c. 185–109 BC), all heads of the Stoa, are extant. However, many fragments (as quotations in other authors, including Cicero, and as pieces of papyrus rolls) do survive.

As was the case with many of the ancient philosophers, the Epicureans and Stoics were interested in the classification of knowledge. Both groups adopted a tripartite division of philosophy, into logic, physics and ethics. For the Epicureans, the chief aim of philosophy was to insure freedom from fear and anxiety; physics, providing knowledge of the natural causes of things, aids the philosopher in the attainment of this goal. For the Stoics, whose aim was 'living in agreement with nature', physics was necessarily important in their philosophy.

Posidonius (c. 135–c. 51 BC) was a student of Panaetius and a teacher of Cicero, who is the source of much of our information about him.[76] He wrote on many topics, including logic, ethics, physics, history and geography; some of the titles of his works include *Physical Discourse*, *On the Cosmos*, *Meteorology*, *On the Size of the Sun*, *On Gods*. According to Cicero (*On the Nature of the Gods* 2.88), Posidonius built an astronomical model. None of his writings are extant and there are serious difficulties in determining which fragments are correctly attributed to him. L. Edelstein noted that the 'disagreement concerning those documents which are supposed to echo the philosophy of Posidonius is so great that it would be quite impossible to assume the Posidonian origin of any passage without incurring objection'. Further, there is disagreement as to the appropriateness of labelling Posidonius a Stoic philosopher.[77]

The Peripatetic, Stoic and Epicurean philosophers all maintained that knowledge is attainable, even though each school had differing views regarding the nature of and means of obtaining such knowledge. In contrast, various sceptical arguments against philosophical dogmatism were advanced, first by Pyrrho of Elis (4th C. BC). The sceptical movement was carried on by others, including Aenesidemus, a former member of the Academy who (in the first century BC) founded the neo-Pyrrhonist school which remained active until at least AD 200. Three works survive written by Sextus Empiricus (a physician and philosopher who lived in the second century AD) which provide an overview of sceptical philosophy and criticisms of other philosophical positions. His work *Against the Professors* includes specific books aimed against grammarians, rhetoricians, geometers, arithmeticians, astrologers and musicians.[78]

The variety of forms in which the ideas of the Hellenistic philosophers have survived and been transmitted is striking, and it is important to recognize that the manner in which ideas have been preserved may affect the ways in which they are read. For many of the major Stoic philosophers, we largely have only fragments of their writings, preserved by other authors who were often polemi-

cal or hostile.[79] The didactic poem, *De rerum natura*, of Lucretius (early to mid-1st C. BC) teaches us much of what we know about Epicurean physics.[80] The intact prose writings of Sextus Empiricus (2nd C. AD) transmit the ideas and arguments of the Pyrrhonian sceptics.[81] In 1884, parts of an inscription were discovered in Turkey, which had been set up in the second century AD by Diogenes of Oenoanda to teach Epicurean philosophy.[82] So, the forms in which the ideas of the ancient philosophers may be read varies considerably.

Marcus Tullius Cicero (106–43 BC) was a Roman orator, statesman, and philosopher who wrote a series of books, mainly dialogues, presenting the principal positions of the leading Hellenistic schools. In addition to Posidonius, he knew some of the other philosophers to whom he refers,[83] and he is an important, if not impartial, source of information regarding the ideas of many Hellenistic philosophers. He particularly sought to make Greek philosophy accessible to Roman readers (*Tusculan Disputations* 1.1) and outlined the positions of various schools on a range of philosophical issues. Although somewhat attracted to Stoic ideas, Cicero regarded himself as a member of the 'New Academy' (*Tusculan Disputations* 2.5, 4.47), the name given to the Academy once it turned to scepticism in the Hellenistic period. Cicero's works of particular interest here include *On the Nature of the Gods* (setting out the views of the Epicureans, Stoics, and Academics) and *On Divination* (on Stoic views). He translated Aratus' poem the *Phaenomena*, to which he added a section on *Prognostica*. Parts of his dialogue the *Republic* are extant, including a portion known as the *Dream of Scipio*, which survived in a version preserved by Macrobius, often dated to AD 400.[84]

Numerous works, on a range of topics and utilizing several different literary formats, survive by the Roman Stoic Lucius Annaeus Seneca (c. AD 1–65). His *Natural Questions*, dealing mainly with natural phenomena and sometimes conveying an ethical message, is one of a number of ancient collections in which questions are posed and answered and problems are presented and solved.[85]

Middle Platonism

As in the case of Seneca, much of the prodigious literary output of Plutarch survives (later 1st to early 2nd C. AD). His *Table Talks* range over a large number of topics, including medicine, zoology, physics and optics, along with philosophy, literature and religion. In his dialogue *On the Face of the Moon*, the speakers discuss the position of the Earth; one of the speakers supports the Aristotelian position, while another argues against it.[86] An important biographer, philosophically Plutarch is usually regarded as a Platonist.

Modern historians use the term 'Middle-Platonic' to refer to the period roughly 80 BC to AD 250.[87] John Dillon has noted during this period the Middle-Platonic philosophers were 'oscillating between the twin poles of attraction constituted by Peripateticism and Stoicism, but adding to the mixture of

these influences a strong commitment ... to a transcendent supreme principle, and a non-material intelligible world above and beyond this one, which stands as a paradigm for it'.[88] The *Didaskalikos (The Handbook of Platonism)* presents a survey of Platonist doctrine, divided into the areas of logic, physics and ethics; the work is now attributed to Alcinous, after its author had long been identified with the Middle Platonist Albinus.[89]

During the Middle Platonic period some thinkers were particularly influenced by what they understood to have been the ideas of Pythagoras; some of the writings of these 'Pythagoreans' survive. Substantial fragments survive of the history of the Academy written by Numenius of Apamea (2nd C. AD) in which he discussed the ideas of Pythagoras and Plato.[90] Moderatus of Gades (c. AD 50–100) produced 'Lectures on Pythagoreanism' in eleven books.[91]

Mathematical writers[92]

Within the ancient Greek tradition, mathematics encompassed a wide range of subjects. The four 'Pythagorean sisters', branches of mathematics, included arithmetic, geometry, astronomy and harmonics,[93] but optics and mechanics were also treated by mathematical writers. It is not always possible, or desirable, to draw a strict boundary between the two largest groups of writers considered to be 'scientific', the philosophers and the mathematical writers. D.H. Fowler has described 'a wide range of different kinds of [mathematical] texts – scientific and commercial, advanced and elementary, abstruse and pedagogic'. Not all of them would have been books.[94]

It is significant that at least some writers considered mathematics to be a branch of philosophy. Plato recommended that future philosopher-kings must first study mathematics before turning to dialectic.[95] Aristotle considered both philosophy and mathematics to be theoretical knowledge.[96] Claudius Ptolemy, who wrote on a wide variety of mathematical topics, including astronomy, harmonics and optics, described mathematics as the highest form of philosophy.[97]

As was the case with early philosophy, the early Greek mathematical tradition was an informal one, which has, for the most part, been completely lost.[98] While their status as 'mathematicians' is debated,[99] the writings of Plato and Aristotle do convey information about contemporary mathematics. The earliest surviving Greek treatises devoted to mathematics, and surviving in their entirety, are two works by Autolycus of Pitane (fl. late 4th C. BC). His *On the Moving Sphere* treats the principal circles of the (celestial) sphere.[100] *On Risings and Settings* deals with the risings, settings and periods of visibility of stars; the work is in two books, actually two versions of the same treatise. That Autolycus was working in what may be cautiously called a 'tradition' is clear from his concerns in another work, now lost but mentioned by Simplicius (*De caelo* 504ff.). Here, Autolycus criticized Eudoxus' system of concentric spheres, arguing that he did not account for differences in the apparent sizes of the heavenly

bodies at different times; further, Autolycus tried to correct this deficiency.[101] Unfortunately, what we know about Eudoxus' own ideas does not come to us from his own writings, but from criticisms and reports in other writers, including Aristotle (*Metaphysics* XII 8). Eudoxus of Cnidos (c. 390–c. 340 BC) was a mathematician with wide-ranging philosophical and scientific interests. He was known in antiquity for his mathematical astronomy and his philosophical hedonism, and placed, if loosely, within the Pythagorean tradition. The long-standing belief that he was a leading member of Plato's Academy has been questioned by some. However, there is evidence that he founded a school at Cyzicus, in the Hellespont, which may have survived into the third century BC. More recently, debate about the correspondence between mathematical models produced by astronomers and the physical motions of astronomical bodies has focused especially on Eudoxus, since he is generally regarded as the first to have used a mathematical model in astronomy. None of his works survives, only accounts and fragments in other ancient authors.[102]

The important role that ancient authors played in preserving the work of their predecessors, in some form, however unreliable, cannot be overestimated. Yet at the same time, in some cases, later works obliterated the writings of predecessors, by causing them to become obsolete. This seems to have been the case with the work known as Euclid's *Elements*. As Fowler has noted, the 13 'books' of the *Elements* cover 'a variety of topics in a recognisably varied range of mathematical and literary styles'. Euclid should be understood as 'the compiler, not the author, of the work; he is believed to have taken source works by other mathematicians and edited them, adapting and rearranging the material, perhaps even inserting new material of his own, to make the complete treatises'.[103] Dating the *Elements* has been a subject of many studies; some time around 300 BC seems most likely.[104] Nine or ten works are attributed to Euclid, including *Data*, *On Divisions of Figures*, *Phaenomena*, *Optics*, and the *Sectio Canonis* (on music).[105]

Archimedes (c. 287–212 BC) is well known both as a practical inventor and as a mathematician of wide-ranging interests. His surviving writings include the following works preserved in Greek: *On the Sphere and Cylinder*, *Measurement of the Circle*, *On Spirals*, *The Equilibriums of Planes*, *Quadrature of the Parabola*, *The Sand-reckoner* (which deals with the expression of very large numbers); *On Conoids and Spheroids*, *Method of Mechanical Theorems*, *On Floating Bodies*;[106] other works, the *Books of Lemmas* and *On the Heptagon in a Circle*, are extant in Arabic. Lost works include most of his writings on astronomy. Cicero (*On the Nature of the Gods* 2.88) described Archimedes' 'achievement in imitating the revolutions of the heavenly sphere' and described (*Republic* I 21–2) two 'sphaerae' made by him. Exactly what these models were is not clear, whether celestial globes, or armillary spheres, or some other type of sphere.

Other important writers on mechanics include Strato of Lampsacus (c. 287–269 BC), head of the Peripatetic School after Theophrastus. He wrote on a wide

variety of topics, including cosmology, zoology, psychology and physics;[107] his ideas about the void are preserved in the *Pneumatica* of Hero of Alexandria (fl. AD 62). Hero wrote widely on mathematics and especially mechanics. His lost works include a commentary on Euclid, of which substantial fragments survive.[108] Extant writings include the *Definitions*, on geometrical terms, and several works on mechanics and instruments (*Pneumatica*, *On Automata-making*, *Mechanica*, *Dioptra*, *Catoptrica*, *Belopoeica*). A group of works on practical measurement (*Geometrica*, *Stereometrica*, *On Measures*) are more likely to have been based on Hero's writings, rather than to have been written by him.[109]

Aristarchus of Samos (3rd C. BC) was a student of Strato of Lampsacus. His astronomical ideas, including his heliocentric hypothesis, are reported by Archimedes (*Sand-reckoner* 4–5) and Plutarch (*On the Face of the Moon* 6); Vitruvius (9.8.1) credits him with the invention of a particular type of sundial and Ptolemy (*Almagest* 3.1) reports that he observed a solstice in 280. His work *On the Sizes and Distances of the Sun and Moon* survives.[110]

Apollonius of Perge (fl. second half of 3rd C. BC) wrote on a range of mathematical topics, including optics and geometry, but much of what we know about his work is through references in other authors, including Ptolemy and Pappus. The first four books of his *Conics* survive; this work is similar to Euclid's *Elements* and Ptolemy's *Almagest* in that it was so successful that it obliterated earlier works on the subject, which, generally, no longer survive.[111]

The writings of Hipparchus (c. 190–after 126 BC), which treated geography, astrology, weather and astronomy, are for the most part lost. Ptolemy is the source of much of our information about Hipparchus, whose only extant work is the *Commentary on the Phaenomena of Eudoxus and Aratus*. Hipparchus' writings display a characteristic of Greek intellectual life, in that they engage with, and in some cases argue against, his predecessors; for example, his *Geography* was a criticism of Eratosthenes' work. Similarly he criticized the description of the constellations by Aratus of Soli (c. 315–240/239 BC), whose *Phaenomena* survives and is a poetic version of a prose work by Eudoxus, having been written at the request of Antigonus (c. 320–239 BC), a ruler of Macedon with interests in philosophy, poetry and history.[112] The popularity of astronomy as a poetic subject is further suggested by Cicero's translation of Aratus' *Phaenomena* (mentioned above) and the *Astronomica* of Manilius (1st C. AD), which seems to have been primarily didactic in aim.[113]

There was clearly a market for pedagogical works. Geminus (c. AD 50) wrote an *Introduction to Astronomy* which provides an overview of the basic concepts of astronomy, geography and the calendar; this survives. His lost works include an epitome of the *Meteorologica* of Posidonius (mentioned by Simplicius in his commentary on Aristotle's *Physics* 291–2).[114]

The topics addressed by mathematical writers were quite varied. Diophantus of Alexandria (between 150 BC and AD 280), wrote several important works on arithmetic. Six books of his *Arithmetica* survive, as well as a work on polygonal numbers. His work has been regarded (along with that of Hero and

Ptolemy) as 'a powerful and profound blend of the earlier Greek geometrical and Babylonian arithmetised methods'.[115] Diodorus of Alexandria (1st C. BC) wrote a work on the construction of sundials by geometrical means, the *Analemma*; a portion is extant in Latin and Arabic versions.[116]

Some authors are notable in the range of mathematical areas that they covered in their work. Claudius Ptolemy, the second-century Alexandrian mathematician, wrote on a wide range of mathematical topics. Several of his works (notably the *Tetrabiblos*, the *Geography*, and the so-called *Almagest*) survived as the standard writings in astrology, geography, and astronomy for many centuries. He wrote on instruments and on other mathematical topics, including optics and harmonics.[117]

Writers on music

Music was, along with arithmetic, geometry and astronomy, one of the four Pythagorean 'sisters', and a number of texts on harmonics survive.[118] Texts by various (not always 'mathematical') authors on harmonic and acoustic theory, including Philolaus, Archytas, Plato, Aristotle, Theophrastus, Aristoxenus, Ptolemy and Aristides Quintilianus have been translated by Andrew Barker in *Greek Musical Writings*.[119]

Writers on geography, meteorology, astrology and alchemy

Some writers on astronomical topics were also interested in geography and meteorology; so, for example, Hipparchus and Ptolemy both wrote on these topics. To the ancient Greeks and Romans, meteorology considered a broader range of phenomena than the weather; some phenomena which would today be considered geological and astronomical were also included. Philosophical writers, including Aristotle and Theophrastus, wrote works on the subject as well.[120]

Interest in meteorological phenomena was sometimes linked to an interest in geography. D.R. Dicks collected the *Geographical Fragments of Hipparchus* (London: University of London Press, 1960).[121] Substantial works survive by Strabo and Ptolemy. The relationship between geography, meteorology, and astronomy was discussed by Ptolemy in his *Tetrabiblos*. Other astrological writers whose works survive include Dorotheus of Sidon (1st or beginning of 2nd C. AD), Vettius Valens (2nd C. AD), Firmicus Maternus (4th C. AD) and Hephaestio (end of 4th C. AD).[122] Many other astrological texts, including numerous fragments, survive.[123]

Authors and texts focused on medical topics are treated elsewhere,[124] however it is well worth noting that some medical writers, including Galen, provide valuable information on other areas of ancient science, including astronomy.[125]

Another group of technical texts is that concerned with alchemy. Many papyri have been been collected, including *Les alchimistes grecs. Tome 1: Papyrus de Leyde, papyrus de Stockholm*, ed. Robert Halleux (1981), Paris; *Indices chemicorum graecorum 1. Papyrus Leidensis. Papyrus Holmiensis*, Rome: Edizioni dell' Ateneo, 1983.[126]

Reaching a wider audience

While many of the above-mentioned works were written for highly knowledgeable readers, other works were written by non-specialists and reflect the general interest of a number of ancient authors in a wide range of subjects, perhaps especially the heavens and the human body. For example, in his *History* Herodotus (5th C. BC), while focusing on the Persian War, conveys much information regarding his own, and others', ideas about various natural phenomena. Aristophanes (died c. 386 BC) poked fun at philosophers interested in nature in his play the *Clouds*, providing a glimpse of how those engaged in scientific theorizing were regarded by some of their contemporaries.[127]

Some Roman writers

The *Historia naturalis* of the Roman encyclopedic author Pliny the Elder (died AD 79) holds an important place in the history of science. While specialists have focused on sections relevant to their own areas of interest, surprisingly little attention has been paid to the work in its entirety or to the author himself. Pliny, who was neither a philosopher nor an expert in any particular area, can be understood as a self-conscious popularizer, providing information to a wide audience composed of other educated men; details of his work habits were reported by his nephew, the younger Pliny (*Epistles* III v). Other members of his class shared Pliny's interest in agriculture, geography and the natural world; some of them also wrote books, including technical manuals. Mary Beagon has argued that the Roman ideal of agricultural life is at the heart of Pliny's philosophy; cultivation of the soil represents the essential harmony between man and nature.[128]

Other Roman agricultural writers whose works survive include Cato (234–149 BC), Varro (116–27 BC), and Columella (1st C. AD); the *Georgics* of the poet Virgil (70–19 BC) must also be mentioned.[129] Like Pliny, other authors produced encyclopaedic works. Celsus (1st C. AD), wrote on topics as diverse as agriculture and rhetoric, but only his section on medicine is preserved.[130]

And while the Roman architect and engineer Vitruvius (1st C. AD) cannot be regarded as an encyclopaedic author, he offered, in his work *On Architecture*, a fairly comprehensive and historical survey of some technical subjects, including astronomy and sundials.[131]

In some cases the modern impression of an author, based on his surviving works, may distort our understanding of his work during his lifetime. Apuleius (born c. AD 125) is today known primarily for his *Metamorphoses*, the sole Roman novel to survive in its entirety. Other works by Apuleius, now lost, included *Quaestiones Naturales*, *Astronomica* and *Arithmetica*, though some fragments survive.[132]

Didactic and scholarly writers

In the second century AD, several influential writers pointed to the beneficial aspects of mathematics for helping people to improve their quality of life. To some extent echoing Platonic sentiments, Theon of Smyrna[133] and Alcinous[134] described the various branches of mathematics as steps in a purification process, necessary preliminaries to initiation into the greater 'mysteries' of philosophy. Nicomachus of Gerasa (between AD 50 and 150) wrote a primer (which is extant) of Pythagorean number theory containing brief allusions to Platonic concepts, in which he mentioned the ethical value of mathematics. For Nicomachus, numerical relations illustrate the primacy of the beautiful, definite, and intelligible over their opposites.[135] These writers were not so much original mathematicians, as popularizers writing elementary handbooks on mathematics.

As part of the developing literary culture of the 'book', the didactic and scholarly traditions produced a variety of handbooks, epitomes, and commentaries; mathematics treatises were often the topic of such treatments. Pappus of Alexandria (fl. AD 320)[136] wrote commentaries on Euclid's *Elements* (of which the part on Book 10 is extant in Arabic), some books of Ptolemy's *Almagest* (of which the sections on Books 5 and 6 survive), Euclid's *Data*, Ptolemy's *Planisphaerium*, and the *Analemma* of Diodorus. Although his commentary on Apollonius' *Conics* is lost, Serenus (4th century AD or later) wrote two works which are extant, *Section of a Cylinder* and *Section of a Cone*.[137]

Theon of Alexandria (fl. AD 364) prepared 'editions' and commentaries on a number of works. Theon's extant works include much of his commentary on Ptolemy's *Almagest*, an introduction and a longer commentary to Ptolemy's *Handy Tables*, and editions of Euclid's *Elements*, *Data* and *Optics*, as well as Ptolemy's *Handy Tables*.[138] His daughter, Hypatia of Alexandria (d. AD 415), who died a pagan martyred by Christians, worked on the third book of the *Commentary on the Almagest*. In addition to her own works, Hypatia produced commentaries on Apollonius' *Conics* and on Diophantus; these are now lost.[139]

Cleomedes has usually been thought to have lived in the second century BC and to have been a follower of Posidonius; however, on astronomical evidence Neugebauer dated him to ca. AD 370). He wrote an astronomical work, Κυκλικὴ θεωρία μετεωρῶν (*Kuklike theoria meteoron = De motu circulari corporum*

caelestium), which in Neugebauer's view 'was meant to be a composition of its own and it is therefore of some interest as a sample of scientific literature in late antiquity.'[140] Eutocius (6th C. AD) produced commentaries on Archimedes' *Sphere and Cylinder*, *Measurement of the Circle* and *Equilibriums of Planes*; his commentary on Apollonius' *Conics* (Books 1–4) survives.[141]

Alan Cameron has argued that the ancient practice of revising and checking an edition of a mathematical text was somewhat different from that applied to literary texts. A special technical term, *paranagignoskein* (αραναγιγνώσκειν), was used to describe the activity of making a mathematical text usable for reading, comprehension, and learning mathematics; this activity sometimes included improving a demonstration or proof and modernizing language.[142]

Cameron suggests that this willingness to amend texts was based on the practical utility of mathematics, for example, for architects. Ineke Sluiter has pointed out that many texts were intended for schools; these school-texts were an 'open' genre, which was more liable to be updated.[143] To some extent, the translation of texts into other languages may be regarded as a way to keep a work current. Some texts survive only in a language into which they were translated.[144]

In some cases later writers played a large role in shaping the way the works of their predecessors were read and regarded. For example, the details of the life of Plotinus (AD 205–269/70) are known mainly through the writings of Porphyry (AD 234–c. 305), who also collected Plotinus' philosophical writings.[145] Porphyry classified these writings according to subject and arranged them into groups of nine; the *Enneads*, as these writings became known, were published ca. 300–305. The essays cover a wide range of philosophical topics; physics and cosmology are treated in *Enneads* 2 and 3 and psychology in *Ennead* 4, while logic, epistemology and metaphysics are the subjects of *Enneads* 5 and 6.[146] Another pupil of Plotinus, the physician Eustochius, also prepared an edition of Plotinus' work.[147]

In addition to his edition of Plotinus' *Enneads*, Porphyry produced a large number of his own writings as well.[148] He wrote commentaries on writings of Plato, Aristotle, Theophrastus and Plotinus, of which only that on Aristotle's *Categories* survives. Other extant works include an incomplete commentary on Ptolemy's *Harmonics*,[149] an embryological treatise (formerly attributed to Galen, *Pros Gauron*),[150] and fragments of a commentary on Plato's *Timaeus*.[151] Porphyry's commentary on Plato's *Timaeus* is likely to have been used by Macrobius in his writing of a *Commentary on the Dream of Scipio*, an exposition of Cicero's *Somnium*. He also wrote a work on vegetarianism, *De abstinentia*.[152]

Iamblichus (probably c. AD 245–c. 325) wrote what seems to have been a popular encyclopaedia on Pythagoreanism, of which several sections, including a *Life of Pythagoras*, three works on mathematics (although the authorship of the *Theological Principles of Arithmetic* is disputed) and the *Protrepticus*, containing valuable extracts from earlier writers, survive. He also produced commentaries on writings by Plato and Aristotle, and several other works, including a work on mystery religions, known as *de mysteriis*.[153]

While commentaries on various types of texts were important from the third century BC, the commentary was a particularly significant genre for scientific writing in the later period. Many of the commentaries on Aristotle have been published in *Commentaria in Aristotelem Graeca* (*CAG*).[154] Although his commentary on Aristotle's *Physics* is lost, Alexander of Aphrodisias (fl. early 3rd C. AD), produced other commentaries on writings by Aristotle, which survive, including those on the *Meteorology* and the *Metaphysics*. Furthermore, some of Alexander's own works, including *On the Soul*, *Ethical Problems*, and *On Fate*, survive.[155] Calcidius (sometimes spelled Chalcidius, 4th C. AD) wrote a commentary on Plato's *Timaeus*; his Latin translation (to 53c only) represented Plato to Latin readers throughout the Middle Ages.[156] The Neoplatonist Proclus (AD 410 or 412–485) was head of the school of philosophy at Athens, the 'Academy', for 50 years. A prolific writer, he produced commentaries on Plato's *Timaeus*, *Republic*, *Parmenides*, *Alcibiades I*, and on Euclid, Nicomachus and Ptolemy, and wrote on theology, physics and astronomy. Many of his works are lost.[157]

The sixth century was a prolific period for commentators. Alexandria was an important site for the commentary tradition. There, Olympiodorus (495/505–after 565) produced various works, including commentaries on several Platonic dialogues and a commentary on Aristotle's *Meteorology*.[158] Another Alexandrian, Iohannes (John) Philoponus (c. 490–570s), wrote commentaries on Aristotle's *Categories*, *Analytica*, *Meteorologica*, *de generatione et corruptione*, *de anima* and *Metaphysics* (unprinted).[159] Philoponus was a Christian whose theological views informed his readings of Plato and Aristotle and shaped his own conception of the physical world. In opposition to Aristotle, Philoponus held the view that the world, and the matter of which it is composed, had a beginning. As Richard Sorabji has noted, Philoponus 'eventually worked out a comprehensive alternative to Aristotelian physics, a scientific world view tailored to cohere with his Christian beliefs'.[160]

Simplicius is primarily known through his commentaries on Aristotle's *On the Heavens*, *Categories*, *Physics* and *On the Soul*, which also contain many fragments of Presocratic philosophers. His other writings which survive include a work on quadratures.[161] The difficulties of attempting to pigeonhole some ancient writers as either a philosopher or a mathematician are underscored in the case of Simplicius, who is described in Arabic sources as a celebrated mathematician.[162] While it is not clear where Simplicius produced his commentaries, some scholars have argued that he lived in Ḥarrân (ancient Carrhae), in what is now Turkey, near the Iraqi border. Evidence suggests that a Neoplatonic school flourished in Ḥarrân up to the tenth century and that this school played an important role in the diffusion of Greek philosophy into Arabic culture.

In this later period particularly, the complex relationships which developed between the Greco-Roman culture of antiquity and the new religions of Christianity and, later, Islam begin to emerge. The survival or loss of ancient writings, including those on scientific topics would, in many cases, have depended on the

attitudes of individual Christians and Moslems. The preservation of pagan texts depended, in large part, on their perceived value within the ascending cultures of Christianity and Islam.

Notes

1. I dedicate this bibliographic essay to the memory of my teacher Professor Duane H.D. Roller and to the memory of my friend Professor Wilbur Knorr.
   I thank Dr Christopher Walker, Dr David Brown, Professor Ineke Sluiter and Dr Sachiko Kusukawa for extremely helpful conversations. Mr Graham Hart, Mr Andrew Hunter, Dr Kusukawa, Professor Sluiter, Professor Sir Geoffrey Lloyd, Professor Vivian Nutton and Professor David Sedley provided valuable comments and suggestions on an earlier version, for which I am grateful. While preparing this essay, I recognized again the extent to which the work of G.T. Toomer continues to serve as an inspiration.
2. William Whewell coined the term 'scientist' in 1840, in his *The Philosophy of the Inductive Sciences founded upon their history*, 2 vols, London: John W. Parker; Cambridge: J. and J.J. Deighton, vol. I, Introduction cxiii (cited in the *Oxford English Dictionary*).
3. Toomer, G.T. (1984), *Ptolemy's Almagest*, New York: Springer-Verlag, p. 56, n. 67, has noted that the standard height for tables in the *Almagest* of 45 lines was 'presumably chosen to conform to some standard height of papyrus roll'.
4. I have taken as my topic scientific books, libraries and collectors in antiquity; accordingly, this section will not deal with the preservation, transmission, collection and editing of ancient texts during either the medieval or the early modern periods.
5. On the topic of the classification of knowledge and expertise see Tatarkiewicz, W. (1963), 'Classification of the arts in antiquity', *Journal of the History of Ideas*, **24**, 231–40; Kühnert, Friedmar (1961), *Allgemeinbildung and Fachbildung in der Antike*, Berlin: Akademie.
6. Lloyd, G.E.R. (1991), 'Introduction' to 'Observational error in later Greek science', in *Methods and Problems in Greek Science: Selected Papers*, Cambridge: Cambridge University Press, p. 301. Lloyd distinguishes between those who engaged in detailed empirical work, and those who did not.
7. The articles included in the section on ancient science in *Isis*, 83 (December 1992) are F. Rochberg, 'Introduction', 547–53, on p. 550; David Pingree, 'Hellenophilia versus the history of science', 554–63; G.E.R. Lloyd, 'Methods and problems in the history of ancient science: the Greek case', 564–77; Heinrich von Staden, 'Affinities and elision: Helen and Hellenocentrism', 578–95; Martin Bernal, 'Animadversions on the origins of Western science', 596–607. For a discussion of the 'Bernal thesis', see Palter, Robert (1993), '*Black Athena*, Afro-centrism, and the history of science', *History of Science*, 31, 227–87; see also Pyenson, Lewis (1993), 'Prerogatives of European intellect: historians of science and the promotion of Western civilisation', *History of Science*, **31**, 289–315. See also Lefkowitz, Mary R. and Rogers, Guy MacLean, (eds), (1996), *Black Athena Revisited*, Chapel Hill: University of North Carolina Press; Lefkowitz, Mary (1996), *Not out of Africa*, New York: Basic Books.
8. An excellent introduction to the field is Neugebauer, O. (1957), *Exact Sciences in Antiquity*, 2nd edn, New York: Dover (1969 reprint); an older work which is not without value is H. and H.A. Frankfort, John A. Wilson, Thorkild Jacobsen, and

William A. Irwin (1977), *The Intellectual Adventure of Ancient Man: An Essay on Speculative Thought in the Ancient Near East*, Chicago: University of Chicago Press; originally published in 1946 and often reprinted.

On Mesopotamia, the seminal works produced by Otto Neugebauer and his colleagues, especially the Assyriologist Abraham Sachs, the historian of mathematics and astronomy Asger Aaboe, and the Egyptologist R.A. Parker should be particularly noted. See Neugebauer, Otto and Sachs, Abraham (1945), *Mathematical Cuneiform Texts*, New Haven, Conn.: American Oriental Society and American Schools of Oriental Research; and the many collaborative papers of Aaboe, Neugebauer and Sachs in the *Journal of Cuneiform Studies* spanning a good 25 years from the 1950s to the 1980s. See also Hunger, H. (1992), *Astrological Reports to Assyrian Kings. State Archives of Assyria, VIII*, Helsinki: Helsinki University Press; Hunger, H. and Pingree, D. (1989), *MUL.APIN: An Astronomical Compendium in Cuneiform. Archiv für Orientforschung*, Beiheft 24, Horn, Austria: F. Berger & Sohne; Neugebauer, O. (1955), *Astronomical Cuneiform Texts*, 3 vols, London: Lund Humphries; Oppenheim, A.L. (1974), 'A Babylonian diviner's manual', *Journal of Near Eastern Studies* (Chicago), 33, 197–220; Høyrup, Jens (1996), 'Changing trends in the historiography of Mesopotamian mathematics: an insider's view', *History of Science*, 34, 1–32. See also Finkel, Irving L. 'On a Late Babylonian medical school', in I. L. Finkel and A. R. George (eds), (forthcoming), *Wisdom, Gods and Literature: Studies in Honour of W.G. Lambert*, Winona Lake: Eisenbraun's.

On Egypt see: Neugebauer, O. and Parker, R.A. (1960–69), *Egyptian Astronomical Texts*, 3 vols: I. *The Early Decans*, 1960. II. *The Ramesside Star Clocks*, 1964. III. *Decans, Planets, Constellations and Zodiacs*, 1969, Providence: Brown University Press; Parker, R.A. (1950), *The Calendars of Ancient Egypt*, Oriental Institute of Chicago, *Studies in Ancient Oriental Civilization* 26, University of Chicago Press.

For editions of and commentaries on Sanskrit scientific texts, David Pingree is practically singlehandedly responsible. See Pingree, David (1970–81), *Census of the Exact Sciences in Sanskrit*, 4 vols, Philadelphia: American Philosophical Society.

On astronomy, readers will find the following generally useful. There are several chapters in Walker, Christopher (ed.) (1996), *Astronomy before the Telescope*, London: British Museum Press, on astronomy in various ancient cultures, which will be useful guides to the sources. See also Kendall, D.G. (ed.) (1974), *The Place of Astronomy in the Ancient World*, Oxford: Oxford University Press; Neugebauer, O. (1975), *A History of Ancient Mathematical Astronomy*, 3 vols, Berlin, Heidelberg and New York: Springer.

Sources for the study of Asian science are far outside of my competence. On Chinese science, readers might begin with the multi-volume work by Joseph Needham and others (1954–), *Science and Civilisation in China*, Cambridge: Cambridge University Press. Currently, there is a good deal of interest in the relations between Chinese and Greek science; see, e.g., Lloyd, G.E.R. (1996), *Adversaries and Authorities: Investigations into Ancient Greek and Chinese Science*, Cambridge: Cambridge University Press.

9. But see Knox, B.M.W. (1968), 'Silent reading in antiquity', *Greek, Roman, and Byzantine Studies*, 9, 421–35.
10. The Greek stone calendars known as *parapegmata* are inscriptions which correlate astronomical and, in some cases, weather phenomena.
11. For example, a Late Babylonian copy, from about 500 BC, is preserved in the British Museum, WA 86378.
12. For details on the production of papyrus, ink and books, see Stephens, Susan A.

(1988), 'Book production', in Michael Grant and Rachel Kitzinger (eds), *Civilization of the Ancient Mediterranean: Greece and Rome*, vol. 1, New York: Charles Scribner's Sons, pp. 421–36. She points out that Pliny's description is not always accurate. See also Reynolds, L.D. and Wilson, N.G. (1991), *Scribes and Scholars: A Guide to the Transmission of Greek and Latin Literature*, 3rd edn, Oxford: Clarendon Press, pp. 1–5; Maehler, Herwig (1996), 'Books, Greek and Roman', in Simon Hornblower and Antony Spawforth, (eds), *The Oxford Classical Dictionary*=(*OCD*), 3rd edn, Oxford: Oxford University Press.

On the history of the papyrus, see Lewis, Naphtali (1974), *Papyrus in Classical Antiquity*, Oxford: Clarendon Press, an enlarged edition of *L'Industrie du Papyrus dans l'Égypte gréco-romaine* (1934) Paris; Lewis, Naphtali (1989), *Papyrus in Classical Antiquity: A Supplement*, Brussels: Fondation Égyptologique du Reine Elisabeth, Papyrologica Bruxellensia 23. The standard introductory work in English on papyrology is Turner, E.G. (1968), *Greek Papyri*, Oxford: Clarendon Press, 2nd edn 1980. See Bagnall, Roger S. (1995), *Reading Papyri, Writing Ancient History*, London: Routledge, for a discussion of historiographical and methodological issues. A particularly useful bibliography may be found in Hans-Albert Rupprecht (1994), *Kleine Einführung in die Papyruskunde*, Darmstadt: Wissenschaftliche Buchgesellschaft.

13. Vase painting of Sappho, mentioned by Stephens (see note 12), p. 426 (with no further reference); also see the picture of a male standing with a roll, in Lewis (see note 12), plate 8, 'The Ancient Book'.
14. Over 1800 rolls, the remains of a library, were found at Herculaneum, a city buried following the eruption of Vesuvius in AD 79; these are particularly useful for historians of ancient philosophy.
15. Reynolds and Wilson (see note 12), p. 24. As Reynolds and Wilson explain, authors could make changes to a text by asking friends to alter their copies, but other copies would remain unchanged.
16. Reynolds and Wilson (see note 12), pp. 4–5.
17. Turner, Eric (1968), *Greek Papyri*, p. 7, citing Beazley, J.D. (1948), 'Hymns to Hermes', *American Journal of Archaeology*, 52, 336–49; Immerwahr, H.R. (1964), 'Book rolls on Attic vases', *Classical, Medieval, and Renaissance Studies in Honor of Berthold Louis Ullman*, Rome, I, 17–48; Immerwahr, Henry R. (1965), 'Inscriptions on the Anacreon Krater in Copenhagen', *American Journal of Archaeology*, 69, 152–54; Immerwahr, Henry R. (1973), 'More book rolls on Attic vases', *Antike Kunst*, 16, 143–47. On our old friend, see Pliny the Younger, *Letters*, Book II.i.
18. Colin H. Roberts, in a study originally published in 1954 and revised with T.C. Skeat in 1983 as *The Birth of the Codex*, London: Oxford University Press for the British Academy, argued that the preference for the codex was linked to the rise and spread of Christianity.
19. Galen *Opera*, ed. K.G. Kühn (1821–33, Leipzig, reprinted 1964–86, Hildesheim: Georg Olms), XII 423, cited in Roberts and Skeat (see note 18), p. 22.
20. Turner, Eric G. (1977), *The Typology of the Early Codex*, Philadelphia: University of Pennsylvania Press, discussed the form, manufacture and contents of early codices.
21. Stephens (see note 12), p. 433. See also Reynolds and Wilson (see note 12), pp. 34–35. On the early history of the book and a discussion of previous scholarship, see Lampe, G.W.H. (1969), *The Cambridge History of the Bible*, vol. 2, Cambridge: Cambridge University Press.
22. The authorship of the Homeric and Hesiodic poems is a subject which has long attracted scholars, as has the oral tradition, particularly of the Homeric poems. These works are widely available in many editions and translations.

23. According to Simplicius (*In Aristotelis Physicorum libros quattuor priores commentaria* (*CAG*), ed. H. Diels (1882), Berlin: Reimer, p. 23, 29), Thales left no writings other than 'the so-called Nautical Star-guide'. Diogenes Laertius (I 23) claimed that the starguide was attributed to Phokos of Samos.
24. For the fragments of Theophrastus' *Physical Doctrines* see Diels, H. (1879), *Doxographi Graeci*, Berlin: Georg Reimer. See also *Theophrastus of Eresus, Sources for his Life, Writings, Thought, and Influence* (1992), ed. and trans. W.W. Fortenbaugh, P.M. Huby, R.W. Sharples and D. Gutas, Philosophia Antiqua 54, Leiden: Brill. In his commentary on Aristotle's *Physics*, Simplicius excerpted some passages from the first book, *On Material Principles*. Mansfeld, Jaap (1992), '*Physikai doxai* and *Problēmata physika* from Aristotle to Aëtius (and beyond)', in William W. Fortenbaugh and Dimitri Gutas (eds), *Theophrastus: his Psychological, Doxographical, and Scientific Writings*, New Brunswick: Transaction, Rutgers University Studies in Classical Humanities V, pp. 63–111, argues that the work was not a history, but rather a collection of physical doctrines and counter-arguments for dialectical use.
25. For more on the doxographers, see Kirk, G.S., Raven, J.E. and Schofield, M. (abbreviated KRS; 1983), *The Presocratic Philosophers*, 2nd edn, Cambridge: Cambridge University Press, pp. 4–6. Hermann Diels collected extant doxographies into his *Doxographi Graeci*; Aëtius is contained in Diels, 273–444. See also Mansfeld, J. (1990), *Studies in the Historiography of Greek Philosophy*, Assen: Van Corcum; Mansfeld, J. and Runia, D.T. (1997), *Aetiana: The Method and Intellectual Context of a Doxographer*, vol. 1, *The Sources*, Leiden: E.J. Brill.
26. On Diogenes Laertius, see Mejer, Jørgen (1978), *Diogenes Laertius and his Hellenistic Background*, Wiesbaden: Franz Steiner. Mejer provides very useful discussion of the doxographical tradition and, more generally, the Hellenistic historiography of philosophy. See also volume 7 of *Elenchos* (1986), *Diogene Laerzio storico del pensiero antico*, containing a series of articles devoted to Diogenes Laertius.
27. It is worth mentioning briefly the doxographical medical text known as *Anonymi Londinensis ex Aristotelis Iatricis Menoniis et aliis medicis eclogae*, published by Diels, H. (1893) in *Supplementum Aristotelicum* III 1 (Berlin); see also Diels, H. (1893), 'Über die Excerpte von Menons Iatrika in dem Londoner Papyrus 137', *Hermes*, 28, 417–20; Manetti, Daniela (1986), 'Note di lettura dell'Anonimo Londinese – Prolegomena ad una nuova edizione', *Zeitschrift für Papyrologie und Epigraphik*, 63, 57–74; Manetti, Daniela (1990), 'Doxographical deformation of medical tradition in the report of the Anonymus Londinensis on Philolaus', *Zeitschrift für Papyrologie und Epigraphik*, 83, 219–33.
28. Hippias and Socrates are both described as having collected excerpts from other authors; Mejer, p. 17, cites Clement of Alexandria's quotation from Hippias (Diels–Kranz 86 B 6; see note 31) and Xenophon's report on Socrates (*Memorabilia* 1.2.56 and 1.6.14); see also Gigon, Olaf (1953), *Kommentar zum ersten Buch von Xenophons Memorabilien*, Basel: Friedrich Reinhardt; Schweizerische Beiträge zur Altertumswissenschaft 5.
29. Skydsgaard, Jens Erik (1968), *Varro the Scholar*, Copenhagen: Analecta Romana Instituti Danici IV Supplementum, p. 102.
30. See Whittaker, John (1989), 'The value of indirect tradition in the establishment of Greek philosophical texts or the art of misquotation', in John N. Grant (ed.), *Editing Greek and Latin Texts: Papers given at the Twenty-Third Annual Conference on Editorial Problems, University of Toronto, 6–7 November 1987*, New York: AMS Press, pp. 63–95.

    The following introductions to ancient historiography contain sections useful even to those interested primarily in scientific writings: Grant, Michael (1995),

Greek and Roman Historians: Information and Misinformation, London: Routledge; Crawford, Michael (ed.) (1983), *Sources for Ancient History*, Cambridge: Cambridge University Press.

31. This work is often referred to in the scholarly literature as 'Diels–Kranz'; it is usually abbreviated 'DK'. References to DK usually take the form 28A12, in which 28 refers to the section on a particular person, A indicates a testimony, and 12 indicates item number twelve. Testimonies are designated by 'A', fragments by 'B'.
32. The 'Introductory note: the sources for Presocratic philosophy' in KRS (pp. 1–6) should be consulted. Kathleen Freeman, *Ancilla to the Pre-Socratic Philosophers*, contains a complete translation of the fragments (B-sections) in Diels–Kranz, *Fragmente der Vorsokratiker*, 5th edn.
33. Collections of fragments of the Presocratics published since the second edition of KRS include: Lesher, J.H. (1992), *Xenophanes of Colophon*, Toronto: University of Toronto Press, Phoenix Presocratics 4; Agustin Garcia Calvo (1985), *Razón común*: edición crítica, ordenación, traducción y comentario de los restos del libro de Heraclito, Madrid: Lucina, Lecturas presocráticas 2 (Greek text with Spanish translation and commentary); ΗΡΑΚΛΕΙΤΟΣ ΠΕΡΙ ΦΥΣΕΩΣ, Roussos, Euangelos N. (ed.) (1987), Athena: Papademas, ΑΡΧΑΙΟΙ ΕΛΛΗΝΕΣ ΦΙΛΟΣΟΦΟΙ ΕΡΜΗΝΕΥΤΙΚΕΣ ΕΚΔΟΣΕΙΣ 1; T.M. Robinson (1987), *Heraclitus: fragments*; a text and translation with a commentary, Toronto and London: University of Toronto, Phoenix pre-Socratics 2 (Phoenix, Supplementary volume 22); Marcel Conche (1987), *Fragments: Héraclite*, including the text with a French translation and commentary 2nd edn, Paris: P.U.F., Épiméthée: essais philosophiques; Neesse, Gottfried (1982), *Heraklit heute: die Fragmente seiner Lehre als Urmuster europäischer Philosophie*, Hildesheim: Georg Olms. (It is difficult to resist speculating that Heraclitus' doctrine regarding flux has somehow influenced scholars' perceived need to continue to establish the text.) See also Huffman, Carl (1993), *Philolaus of Croton: Pythagorean and Presocratic, a Commentary on the Fragments and Testimonia with Interpretive Essays*, Cambridge: Cambridge University Press; those particularly interested in Pythagoreanism should consult Burkert, Walter (1972), *Lore and Science of Ancient Pythagoreanism*, trans. Edwin L. Minar, Cambridge, Mass.: Harvard University Press.
34. *Suidae lexicon*, ed. A. Adler (1928–38), 5 vols, Leipzig: Teubner.
35. On genuineness, see Sandys, John Edwin (1903–8), *A History of Classical Scholarship*, 3 vols, Cambridge: Cambrige University Press, I: 84; Bonitz, Hermann (1870), *Index Aristotelicus*, Berlin: G. Reimer, Graz: Akademische Druck- und Verlagsanstalt, 1955, 2nd edn rpt; Heitz, Emil (1865), *Die verlorenen Schriften des Aristoteles*, Leipzig: Teubner.

    Robinson, R., 'Plato', *OCD* 2nd edn, N.G.L. Hammond and H.H. Scullard (eds), Oxford: Clarendon Press, has noted that 'even those who reject them [the letters] appear to think the *Seventh* reliable in its history.'

    Pfeiffer, Rudolph, (1968), *History of Classical Scholarship: From the Beginnings to the End of the Hellenistic Age*, Oxford: Clarendon Press, pp. 65–66, notes that 'there is no evidence about the early fortunes of Plato's dialogues; but it is a fair guess that the first generation of his pupils tried to collect, to arrange, and to copy the autographs of the master, and that this "Academy Edition" became the basis of all the later ones'. Here he cites von Wilamowitz-Moellendorff, Ulrich (1920), *Platon* II, Berlin: Weidmann, p. 324, and also (against the assumption of a fundamental edition made by the Academy after Plato's death) Jachmann, Günther (1941), 'Der Platontext', *Nachrichten von der Akademie der Wissenschaften in Göttingen, Philologisch-historische Klasse* nr 7, 334, who argued that Aristophanes of Byzantium was responsible for the first edition (cf.

Pfeiffer, pp. 196 f.). On p. 246, Pfeiffer states that 'not until the first century BC did Academy and Peripatos begin to edit and explain the writings of their own founders.'

Diogenes Laertius (III 37) mentions that 'some say that Philippus of Opus copied out the *Laws*, which were left upon waxen tablets'. Here and elsewhere in this essay, the translation from Diogenes Laertius is by R.D. Hicks (1925, rpt 1980), *Diogenes Laertius: Lives of Eminent Philosophers*, 2 vols, Cambridge, Massachusetts: Harvard University Press, Loeb Classical Library.

See also Alline, Henri (1915), *Histoire du texte de Platon*, Paris: Librairie Ancienne Honoré Champion, Bibliothèque de l'école des hautes études 218; Bickel, Ernst (1944), 'Geschichte und Recensio des Platontextes', *Rheinisches Museum für Philologie*, 92, 97–159; Philip, J.A. (1970), 'The Platonic Corpus', *Phoenix*, 24, 296–308.

Ancient authors who wrote on the corpus include Dionysius of Halicarnassus *Epistula ad Pompeium*, 758–61; *On Arrangement of Words (De compositione verborum)*, 208–9; Quintilian 10.1.81; 'Longinus' *On the Sublime*, 4, 28, 29, 32.

Sandys, I: 85, mentions the earliest extant manuscript of any part of Plato as having been found in Egypt: 'It is the Petrie papyrus from Gurob in the Faiyûm, containing about 12 columns of the *Phaedo*, being portions of a neatly written trade-copy assigned to the middle of the third century BC.'

36. Diogenes Laertius III 48.
37. Diogenes Laertius III 56; cf. III 56–62 on the divisions made by Thrasyllus and Aristophanes the Grammarian (into trilogies). See also Sluiter, Ineke (forthcoming) 'Dialectics as genre: some aspects of secondary literature and genre in antiquity', in Mary Depew and Dirk Obbink (eds), *Matrices of Genre*, Cambridge, Mass.: Harvard University Press, on the grouping of literary texts into trilogies and tetralogies.
38. Diogenes Laertius III 66.
39. In the modern period, ordering the dialogues chronologically according to the date of writing is an activity which has occupied the efforts of many scholars; generally, a rough division into three periods (early, middle, late) is accepted, but, in some cases, the dating of individual dialogues continues as a topic of study. For an overview of the scholarship, consult Thesleff, H. (1982), *Studies in Platonic Chronology*, Helsinki: Societas Scientiarum Fennica Commentationes humanarum litterarum 70; and Brandwood, Leonard (1992), 'Stylometry and chronology,' in Richard Kraut (ed.), *The Cambridge Companion to Plato*, Cambridge: Cambridge University Press, pp. 90–120. Brandwood is also the author (1990) of *The Chronology of Plato's Dialogues*, Cambridge: Cambridge University Press; Brandwood's approach has been challenged by some, including Keyser, Paul (1992), in 'Stylometric method and the chronology of Plato's works', *Bryn Mawr Classical Review*, 3, 58–74. The *Cambridge Companion to Plato* contains a very useful bibliography, including a section on chronological studies (pp. 501–2). The 'Introduction to the study of Plato', by Richard Kraut, in the same volume, is a good starting point.
40. Diogenes Laertius (III 48) claimed that while 'Zeno the Eleatic was the first to write dialogues. ... In my opinion Plato, who brought this form of writing to perfection, ought to be adjudged the prize for its invention as well as for its embellishment.'
41. For an overview of the individual dialogues, readers may consult the articles on 'Plato' in the *Dictionary of Scientific Biography* (*DSB*) and the *Encyclopedia of Philosophy*. Many editions and translations exist. The Oxford Classical Text edition, edited by J. Burnet, is considered a standard; there is a useful index included in the translations edited by Edith Hamilton and Huntingdon Cairns

(1961), *The Collected Dialogues of Plato*, Princeton: Princeton University Press, Bollingen Series 71. The Bibliography to the *Cambridge Companion* is also very helpful. NB: while readers will have recourse to any number of editions and translations, references to Plato's works cite 'Stephanus pages'. This convention offers readers a uniform system of reference, by providing in the margins of modern editions the page references to the edition of Plato's writings published in 1578 by Henri Estienne (c. 1528/31–1598). This edition was, for more than two centuries, the standard. The name 'Stephanus' comes from the latinized form of 'Estienne'.

42. Some scholars have pointed to the passage at 529a–530b as representing Plato's own views on astronomy; however, the meaning of the passage itself has been variously construed. See the articles by Vlastos, Gregory, 'The role of observation in Plato's conception of astronomy', pp. 1–31, and Mourelatos, Alexander P.D., 'Plato's "real astronomy": Republic 527d-531d', pp. 33–73, in John Anton (ed.) (1980), *Science and the Sciences in Plato*, New York: Eidos Press; see also Duhem, Pierre (1969), *To Save the Phenomena: an Essay on the Idea of Physical Theory from Plato to Galileo*, trans. Edmund Doland and Chaninah Maschler, Chicago: University of Chicago Press, trans. of *ΣΩΖΕΙΝ ΤΑ ΦΑΙΝΟΜΕΝΑ: essai sur la notion de théorie physique de Platon à Galilée*, *Annales de philosophie chrétienne* (1908) ser. 4, VI and reprinted in that year under the same title by A. Hermann et Fils. See now Gregory, Andrew (1996), 'Astronomy and observation in Plato's *Republic*', *Studies in History and Philosophy of Science*, 27, 451–71.
43. Mueller, Ian (1992), 'Mathematical method and philosophical truth', in Kraut, *Companion to Plato*, pp. 170–99; Burnyeat, Myles (1987), 'Platonism and mathematics: a prelude to discussion', in Andreas Graeser (ed.), *Mathematics and Metaphysics in Aristotle*, Bern and Stuttgart: P. Haupt, pp. 213–40. Cherniss, Harold (1951), 'Plato as mathematician', *Review of Metaphysics*, 4, 395–425, reprinted in Cherniss, Harold (1977), *Selected Papers*, ed. Leonardo Tarán, Leiden: E.J. Brill, pp. 222–52. Cornford, Francis MacDonald (1932), 'Mathematics and dialectic in the *Republic* VI–VII,' *Mind*, 41, 37–52, 173–90; reprinted in *Studies in Plato's Metaphysics*, ed. R.E. Allen, London: Routledge & Kegan Paul, pp. 61–96.
44. In addition to editions and translations mentioned above, see Cornford, Francis Macdonald (1937), translator and commentator, *Plato's Cosmology: The 'Timaeus' of Plato*, New York: Humanities Press; London: Routledge and Kegan Paul; reprinted Indianapolis: Bobbs–Merrill, 1975. The *Timaeus* was particularly important during the Middle Ages; as a creation story, it was not necessarily objectionable to Christians.
45. Riginos, A.S. (1976), *Platonica: The Anecdotes Concerning the Life and Writings of Plato*, Leiden: Brill.
46. Findlay, J.N. (1974), 'Appraisal of Platonism and its influence', in *Plato: The Written and Unwritten Doctrines*, New York: Humanities Press, pp. 350–412. The work of Konrad Gaiser, *Platons ungeschriebene Lehre* (Stuttgart: Ernst Klett Verlag, n.d.) is representative of the approach of the Tübingen school; see also Gaiser, K. (1963), *Testimonia Platonica: Quellentexte zur Schule und mündlichen Lehre Platons*, Stuttgart: Ernst Klett.

While this is the case with other ancient authors as well, the importance of Plato's 'unwritten opinions' is worthy of consideration for several reasons. First, Plato himself made much of the limitation of the written word, emphasizing the superiority of oral communication, especially with regard to education (*Phaedrus* 274b–78b). See Kraut (see note 39), p. 48, n. 69, for bibliographical suggestions, and Guthrie, W.K.C. (1962–81), *History of Greek Philosophy*, 6 vols, Cambridge: Cambridge University Press, vol. 5, chap. 8 (on 'Plato's "unwritten" metaphysics') for a guide to some of the literature.

Furthermore, since Plato wrote dialogues, in which he himself never figured directly as a speaker, it has been argued that it is difficult to determine what Plato himself believed and advocated. Additionally, given the oral character of the Greek philosophical enterprise, it seems unwise to ignore 'oral' testimony.

47. For a discussion of the evidence of the Academy in Plato's time, see Fowler, D.H. (1987), *The Mathematics of Plato's Academy: A New Reconstruction*, Oxford: Clarendon Press, chapters 4 and 6. See also Cameron, Alan (1969), 'The last days of the Academy in Athens', *Proceedings of the Cambridge Philological Society* 195 (New Series 15), pp. 7–29; Sedley, D. (1981), 'The end of the Academy', *Phronesis*, 67–75. See Glucker, J. (1978), *Antiochus and the Late Academy*, Göttingen: Vandenhoeck & Ruprecht = *Hypomnemata* 56, on the disappearance of the Academy as an institution in the early first century BC. See also Blumenthal, H.J. (1993), *Soul and Intellect: Studies in Plotinus and Later Neoplatonism*, Aldershot: Variorum.
48. Lang, P. (1911), *De Speusippi Academici Scriptis*, Bonn dissertation; reprinted Hildesheim: Georg Olms, 1965; Tarán, L. (1981) *Speusippus of Athens: a Critical Study with a Collection of the Related Texts and Commentary*, Leiden. See also Dancy, R.M. (1991), *Two Studies in the Early Academy*, Albany, NY: State University of New York Press, which is primarily concerned with Speusippus and Eudoxus. Eudoxus' relationship to the Academy is unclear; he will be discussed below in the section on mathematical writers, even though he had other philosophical interests.
49. Diogenes Laertius IV 10–14.
50. Pines, Shlomo (1961), 'A new fragment of Xenocrates and its implications', *Transactions of the American Philosophical Society*, n.s. 51, pt 2, 3–34; Heinze, R. (1892), *Xenocrates: Darstellung der Lehre und Sammlung der Fragmente*, Leipzig, rpt. Hildesheim: Olms, 1965; Parente, Margherita Isnardi (ed.) (1981), *Senocrate–Ermodoro: Frammenti*, Naples: Bibliopolis.
51. Pfeiffer, p. 66, on Aristotelian writings; text of the ancient lists of Aristotelian writings in Rose, Valentin (1886), *Aristotelis qui ferebantur librorum fragmenta*, Leipzig: B.G. Teubner, pp. 3–22 (previously published with the title *Aristoteles pseudepigraphus*, Leipzig, 1863); cf. Moraux, Paul (1951), *Les Listes anciennes des ouvrages d'Aristote*, Louvain: Université de Louvain, Institut Supérieur de Philosophie, Aristote: Traductions et études; see also Moraux, Paul (1973), *Der Aristotelismus bei den Griechen I*, Berlin: de gruyter, on the origins of the corpus.

    Modern editions of the works of Aristotle include Oxford, Teubner, Les Belles Lettres. The Oxford translations are still useful, especially for the notes, which are not contained in *The Complete Works of Aristotle: the Revised Oxford Translation*, ed. Jonathan Barnes (1984), 2 vols, Princeton: Princeton University Press, Bollingen Series 71, 2, a revised version of *The Works of Aristotle Translated into English*, ed. W.D. Ross, various translators, 12 vols, Oxford: Clarendon Press, 1908–52. Individual works are available in the Loeb Classical Library series, published by Harvard University Press and Heinemann. Critical editions of the Greek text of individual works are published in the Scriptorum Classicorum Bibliotheca Oxoniensis (Oxford Classical Texts) series, Oxford: Clarendon Press.

    Citations of ancient authors are often difficult to decipher; there is no one standard system. For Aristotle, pagination in the edition by Bekker, I. (1831), *Aristotelis Opera*, provides one system. Jonathan Barnes has provided a handy introduction to some of the intricacies and inconsistencies in the section 'Aristotle's writings', in Barnes, Jonathan (ed.) (1995), *The Cambridge Companion to Aristotle*, Cambridge: Cambridge University Press.
52. Other ancient lists survive as well; see Düring, Ingemar (1957), *Aristotle in the Ancient Biographical Tradition*, Göteborg: Studia graeca et Latina gothoburgensia V; cf. Plezia, M. (1962), *Gnomon*, 34, 126–32, review of Düring.

53. Barnes, *Companion* (see note 51), pp. 13–15.
54. The sections on logic (pp. 308–24), philosophy of science (pp. 324–32), science (pp. 332–37), psychology (pp. 337–45) and metaphysics (pp. 345–57) are particularly useful.
55. See, for example, Düring, Ingemar (1944), *Aristotle's Chemical Treatise Meteorologica Book IV*, Göteborg.
56. Wehrli, F. (1944–59), *Die Schule des Aristoteles: Texte und Kommentar*, 10 vols, Basel: B. Schwabe Brink, K.O. (1940), 'Peripatos', *Paulys Real-encyclopädie der classischen Altertumswissenschaft*, supp. 7, 899–949; Lynch, J.P. (1972), *Aristotle's School: a Study of a Greek Educational Institution*, Berkeley: University of California Press.
57. Wehrli, F. (ed.) (1955), *Eudemos von Rhodos, Die Schule des Aristoteles: Texte und Kommentar* 8, Basel: B. Schwabe; Spengel, L. (1866), *Eudemi Rhodii Peripatetici fragmenta*, London: Williams and Norgate.
58. See Keaney, J.J. (1968), 'The early tradition of Theophrastus' *Historia plantarum*', *Hermes*, 96, 293–98. There has recently been a great deal of interest in Theophrastus, resulting in a number of new editions and translations of his work; what follows is a selection of some recent publications. *Theophrastus of Eresus: on his life and work*, ed. William W. Fortenbaugh together with Pamela M. Huby and Anthony A. Long (1985), New Brunswick, USA: Transaction Books, Rutgers University Studies in Classical Humanities 2; *Recherches sur les plantes (De historia et causis plantarum = Enquiry into plants)*, ed. and trans. Suzanne Amigues (1988), Paris: Les Belles Lettres, Collection des universités de France; *Theophrastean Studies: on Natural Science, Physics and Metaphysics, Ethics, Religion, and Rhetoric*, ed. William W. Fortenbaugh and Robert W. Sharples (1988), New Brunswick, USA: Transaction Books, Rutgers University Studies in Classical Humanities 3; *Theophrastus: his Psychological, Doxographical, and Scientific Writings*, ed. William W. Fortenbaugh and Dimitri Gutas (1992), New Brunswick, NJ: Transaction, Rutgers University Studies in Classical Humanities 5. *Theophrastus of Eresus, Sources for his Life, Writings, Thought, and Influence*, ed. and trans. by W.W. Fortenbaugh, P.M. Huby, R.W. Sharples and D. Gutas (1992), Philosophia Antiqua 54, Leiden: Brill, containing Greek, Latin and Arabic texts with English translation; Pt 1: life, writings, various reports, logic, physics, metaphysics, theology, mathematics; Pt 2: psychology, human physiology, living creatures, botany, ethics, religion, politics, rhetoric and poetics, music, miscellanea; *Metaphysics*, with an introduction, translation, and commentary by Marlein van Raalte (1993), Leiden and New York: E.J. Brill, Mnemosyne: bibliotheca classica Batava, Supplementum 125; Sharples, R.W. (1995), *Theophrastus of Eresus: Sources for his Life, Writings, Thought and Influence.* Commentary volume 5: sources on biology: human physiology, living creatures, botany – texts 328–435, Leiden; New York: E.J. Brill, Philosophia antiqua 64. Theophrastus' *Characters* is probably his most widely known work. Ussher, R.G. (ed.) (1993), *The Characters of Theophrastus*, new edn, London: Bristol Classical Press, previous edn Basingstoke: Macmillan, 1960; *The Characters of Theophrastus*: a reproduction in facsimile from an edition printed in London in 1831, with original line engravings and a new introduction, London: Open Gate, 1991, facsimile reprint of the first part of: *The Characters of Theophrastus*, translated, and illustrated by physiognomical sketches by I. Taylor (1831), London: A.J. Valpy; *Theophrastus Characters; Herodas Mimes; Cercidas and the Choliambic poets*, ed. and trans. Jeffrey Rusten, I.C. Cunningham and A.D. Knox (1993), 2nd edn, Cambridge, Mass.: Harvard University Press, Loeb Classical Library.
59. There is no evidence of a public library at Athens, Reynolds and Wilson (see note 12), p. 5.

60. See Ross, W.D. (1970), 'Aristotle', in *OCD*, 2nd edn, p. 115: 'he collected manuscripts – the prototype of all the great libraries of antiquity – maps, and probably a museum of objects to illustrate his lectures, especially those on zoology. Alexander is said to have given him 800 talents to form the collection, and to have ordered the hunters, fowlers, and fishermen of the Empire to report to Aristotle any matters of scientific interest.' Aristotle also formed a collection of the constitutions of the Greek city-states.

    Lynch, John Patrick (1972), *Aristotle's School* (see note 56), Berkeley: University of California, p. 149, has explained that 'the proliferation of libraries in the third century BC implies the existence of multiple copies of books'. On other libraries see Parsons, E.A. (1952), *The Alexandrian Library*, New York: American Elsevier. Testimonia on private and city libraries are gathered by Platthy, J. (1968), *Sources on the Earliest Greek Libraries*, Amsterdam: Adolf M. Hakkert.
61. Knox, B.M.W. (1985), 'Books and readers in the Greek world: from the beginnings to Alexandria', in P.E. Easterling and B.M.W. Knox (eds), *Cambridge History of Classical Literature*, Cambridge: Cambridge University Press, p. 13; paperback edition, 1989, Cambridge: Cambridge University Press, vol. 1, part 4: The Hellenistic Period and the Empire, p. 166.
62. Thomas, Rosalind (1992), *Literacy and Orality in Ancient Greece*, Cambridge: Cambridge University Press.
63. Diogenes Laertius V 51–57 (the will of Theophrastus), V 61–64 (the will of Strato), V 69–74 (the will of Lyco).
64. Pfeiffer (see note 35), p. 65.
65. Strabo XIII 1.54; Plutarch *Sulla* 26. Lynch, *Aristotle's School* (see note 56), provides a useful summary of some of the modern scholarship, p. 147, n. 20 and n. 21. See Bidez, J. (1943), *Un singulier naufrage littéraire dans l'antiquité*, Brussels: J. Lebèque & Cie. Düring, I., *Aristotle and the Ancient Biographical Tradition*, pp. 337–38, 382–84, 392–95, 412–25; E. Zeller (1897), *Aristotle and the Earlier Peripatetics*, trans. B.F.C. Costelloe and J.H. Muirhead, 2 vols, London: Longmans, Green, vol. 1, pp. 137–60; Susemihl, F. (1891–92), *Geschichte der griechischen Literatur in der Alexandrinerzeit II*, Leipzig: Teubner, pp. 296–301; Chroust, A.-H. (1962), 'The miraculous disappearance and recovery of the Corpus Aristotelicum', *Classica et Mediaevalia*, 23, 50–67; Shute, R. (1888), *On the History of the Process by which the Aristotelian Writings Arrived at their Present Form*, Oxford: Clarendon Press; Düring, I. (1954), 'Von Aristoteles bis Leibniz', *Antike und Abendland*, 4, 118–54, reprinted in P. Moraux (ed.) (1968), *Aristoteles in der neueren Forschung*, Darmstadt, pp. 250–313; Moraux, P., *Les Listes anciennes des ouvrages d'Aristote* (see note 51), especially the conclusions on pp. 312–21; Düring, I., (1956), 'Ariston or Hermippos?', *Classica et Mediaevalia*, 17, 11–21; Keaney, J.J., (1963), 'Two notes on the tradition of Aristotle's writings', *American Journal of Philology*, 84, 52–63.
66. Reynolds and Wilson (see note 12), p. 7, who are also helpful on the work of the Library, and the librarians. They note that 'the number of volumes is variously estimated by the ancient sources, but owing to the inaccuracy with which all large figures given by classical authors are transmitted it is difficult to calculate the true figure. If we accept as true the tradition that in the third century the library contained 200,000 or 490,000 volumes (Eusebius, *Praep. Evang.* 350B, Tzetzes, *Prolegomena de comoedia*), allowance must be made for the small capacity of each roll of papyrus.' See also Fraser, P.M. (1972), *Ptolemaic Alexandria*, 3 vols, Oxford: Clarendon Press, chap. 6 on the Museum and the Library, and chap. 8 on Alexandrian scholarship; readers are cautioned that his account of Alexandrian science (chap. 7) tends to be historiographically out-of-date, especially his discussion of 'The False Sciences'. On the Library, see Canfora, Luciano (1989), *The*

Vanished Library: a Wonder of the Ancient World, trans. Martin Ryle, Berkeley: University of California Press.

67. Sandys (see note 35), pp. 148ff.; Reynolds and Wilson (see note 12), p. 17. While much of what we know about the Alexandrian library comes to us from literary descriptions, excavations undertaken by German archaeologists in the nineteenth century unearthed some parts of the Pergamene library. Nevertheless, much more is known about the Alexandrian Library.
68. Pfeiffer (see note 35), pp. 102–3.
69. E.G. Turner, *Greek Papyri* (see note 12), pp. 112–13. See also van Groningen, B.A. (1963), 'Ekdosis', *Mnemosyne*, 16, 1–17.
70. The fragment on the measurement of the Earth may be found in Ivor Thomas (ed. and trans.) (1939, 1941), *Selections illustrating the History of Greek Mathematics*, 2 vols, Cambridge, Mass: Harvard University Press; London: William Heinemann, Loeb Classical Library, I: 100, 290 ff.; II: 260 ff.
71. Barnes, J., Mansfeld, J. and Schofield, M. (eds), *The Cambridge History of Hellenistic Philosophy*, Cambridge, forthcoming.
72. The character of the various ancient 'schools' of philosophy is a topic of study unto itself. Anthony Long and David Sedley (see note 81) helpfully explain (I: 5–6): 'What was a "school"? Not, in general, a formally established institution, but a group of like-minded philosophers with an agreed leader and a regular meeting place, sometimes on private premises but normally in public. School loyalty meant loyalty to the *founder* of the sect – Zeno for the Stoa, Epicurus for the Garden, Socrates and Plato for the Academy – and it is in that light that the degree of intellectual independence within each school must be viewed. It was generally thought more proper to present new ideas as interpretations or developments of the founder's views than as criticisms of him ... . The virtually unquestioned authority of the founder within each of the schools gave its adherents an identity as members of a 'sect' (*hairesis*), readily recognizable by their labels 'Stoic', 'Epicurean', 'Academic' or 'Pyrrhonist". See also Wycherly, R.E., 'Peripatos: The Athenian philosophical scene', *Greece and Rome*, 2nd series, 8, (1961), 152–63 and 9 (1962), 2–21.
73. Various editions and translations of the extant writings of Epicurus may be found. The standard edition by Usener, H. (1887), *Epicurea*, Leipzig: Teubner, does not contain the papyrus fragments; see also Bailey, Cyril (ed.) (1926), *Epicurus: The Extant Remains*, Oxford: Clarendon Press. In 1888 C. Wotke discovered 81 maxims in a Vatican manuscript; these have become known as the *Vatican Sayings [Sententiae Vaticanae]*, ed. P. von der Mühll (1922), Leipzig: Teubner; see Geer, Russel M. (1964), *Letters, Principal Doctrines, and Vatican Sayings*, New York: Library of Liberal Arts, for an English translation. Papyrus fragments found at Herculaneum of Epicurus' *On Nature* have been edited by Arrighetti, G. (1973), *Epicuro Opere*, 2nd edn, Turin; other editions and translations include Bollack, Jean and Laks, André (eds) (1978), *Epicure à Pythocles: sur la cosmologie et les phénomènes météorologiques*, Lille: Publications de l'Université de Lille III, Cahiers de philologie 3; *Lettres et maximes*, ed. and trans. Marcel Conche (1987, new edn), Paris: Presses universitaires de France; *The Epicurus reader: selected writings and testimonia*, trans. and ed. Brad Inwood and L.P. Gerson; introduction D.S. Hutchinson (1994), Indianapolis; Cambridge: Hackett.

    See also *Epicureanism: Two Collections of Fragments and Studies* (1987), New York: Garland Pub., facsimile reprints of *Metrodori Epicurei fragmenta*, ed. Alfred Koerte (1890–), Leipzig: Teubner and *L'Epicureo Demetrio Lacone*, ed. V. de Falco (1923), Naples: Cimmaruta; Rodis-Lewis, Genevieve (1975, 1993 rpt), *Epicure et son école*, Gallimard; Castner, Catherine J. (1988), *Prosopography of*

Roman Epicureans from the second century BC to the second century AD, Frankfurt am Main; New York: P. Lang, Studien zur klassischen Philologie 34.

74. Many editions and translations are available of Lucretius *De rerum natura* (*On the Nature of Things*); a frequently cited text is that of Bailey, Cyril (1947), *Titi Lucreti Cari: de rerum natura libri sex*, 3 vols, Oxford: Clarendon Press.
75. Gigante, Marcello (1987), *La bibliothèque de Philodème et l'`épicurisme romain*, Paris: Les Belles Lettres, Collection d'études anciennes 56, cf. Gigante, Marcello (1990), *Filodemo in Italia*, Firenze: Le Monnier, Bibliotechnia del saggiatore 49 and Gigante, Marcello (1995), *Philodemus in Italy: The Books from Herculaneum*, trans. Dirk Obbink, Ann Arbor: University of Michigan. Of Philodemus' own writings see, for example, *On signs*, Phillip and Estelle De Lacy (eds) (1978), *Philodemus, On methods of inference*, 2nd edn, Naples: Bibliopolis.

    Reynolds and Wilson (see note 12), p. 18, note that 'the writings of Epicurus were studied very closely by his later disciples, and corrupt copies posed many problems. One surviving work, an essay by Demetrius Lacon perhaps written c. 100 BC (P. Herculaneum 1012), displays considerable sophistication in dealing with these questions; it several times refers to faulty copies; it considers variation between copies; in one passage there is talk of damage caused by book-worms and the subsequent attempt of a reader to put right a defective text.' As this example demonstrates, 'the critical methods of Alexandria were not simply a tool to be used by students of literature'.
76. Cicero *On Divination* 1.3.6 and *On the Nature of the Gods* 1.3.6; see also Plutarch *Cicero* 4; Diogenes Laertius VII 138–49.
77. Kidd, I.G. and Edelstein, L. (1972, 2nd edn 1989) have edited *Posidonius: The Fragments*, Cambridge: Cambridge University Press. Edelstein, passage quoted from his surviving papers, reprinted by Kidd in *Posidonius* I, p. xvi. The textual problems and ensuing controversies were discussed by Kidd (1936) in his 'Introduction' to *Posidonius* I, and by Edelstein in 'The philosophical system of Posidonius', *American Journal of Philology*, 57, 286–325. Edelstein went so far, when speaking of Posidonius' physics, as to remark that 'compared with the general Stoic system it is heretical', I.G. Kidd, 'Posidonius', *OCD* 3rd edn, has recently noted that 'Posidonius has been dubbed unorthodox in his Stoicism, but this is a misconception. He was not so regarded by his contemporaries, and he did not diverge from the fundamental tenets'.
78. Sextus Empiricus *Works*, ed. and trans. R.G. Bury (1933–49), 4 vols, Cambridge: Harvard University Press, London: William Heinemann, Loeb Classical Library.
79. von Arnim, H. (1903–24), *Stoicorum veterum fragmenta*, 4 vols, Leipzig: Teubner.
80. Numerous editions and translations are available of Lucretius (see note 74).
81. A very useful collection of Stoic, Epicurean, Pyrrhonist and Academic texts may be found in Long, A.A. and Sedley, D. (1987), *The Hellenistic Philosophers*, 2 vols, Cambridge: Cambridge University Press. The first volume contains translations of the principal sources, together with a philosophical commentary; the second volume is devoted to the Greek and Latin texts, with accompanying notes, and very useful bibliographies. While Long and Sedley are primarily interested in issues relating to the history of philosophy, rather than the history of science, the two volumes are invaluable.
82. I am grateful to Professor Vivian Nutton for bringing this example to my attention. See Chilton, C.W. (1963), 'The inscription of Diogenes of Oenoanda', *American Journal of Archaeology*, 67, 285–86; Chilton, C.W. (1967), *Diogenis Oenoandensis fragmenta*, Leipzig: Teubner; Casanova, Angelo (ed.) (1984), *I frammenti di Diogene d'Enoanda*, Florence: Università degli studi di Firenze, Studi e Testi 6; Smith, Martin Ferguson (ed.) (1993), *The Epicurean Inscription*, Naples: Bibliopolis.

83. Long and Sedley (see note 81), p. 493. See also Fortenbaugh, William W. and Steinmetz, Peter (eds) (1989), *Cicero's Knowledge of the Peripatos*, New Brunswick, New Jersey: Transaction Publishers, Rutgers University Studies in Classical Humanities 4.
84. Various editions and translations of Cicero's works are available; readers may find the Loeb Classical Library texts convenient.

    On Macrobius, see Cameron, A. (1966), 'The date and identity of Macrobius', *Journal of Roman Studies*, 56, 25–38; Ambrosius Theodosius Macrobius, *Opera*, ed. J. Willis (1963), 2 vols, Leipzig: Teubner; *Saturnalia* ed. J. Willis, vol. 1, 2nd edn (1970), Stuttgart, Leipzig: Teubner, with corrections, 1994 (a symposium on a variety of topics); *Commentarii in somnium Scipionis*, ed. J. Willis, vol. 2, 2nd edn (1970), Stuttgart, Leipzig: Teubner; *Commentary on the Dream of Scipio*, trans. William Harris Stahl (1952), New York: Columbia University Press; *Macrobii Ambrosii Theodosii Commentariorum in somnium Scipionis libri duo*, trans. Luigi Scarpa (1981), Padua: Liviana.
85. Hine, Harry M. (1996), *Studies in the Text of Seneca's Naturales quaestiones*, Stuttgart: Teubner, Beiträge zur Altertumskunde 72; *L. Annaei Senecae Naturalium quaestionum libros*, ed. Harry M. Hine (1996), Stuttgart: Teubner; *Naturales quaestiones. Liber 2. An edition with commentary of Seneca, Natural questions, book two*, ed. Harry M. Hine (1981) Salem, New Hampshire: Ayer, revision of Harry M. Hine's PhD thesis (Oxford, 1975); *Questioni naturali di Lucio Anneo Seneca*, ed. Dionigi Vottero (1989), Turin: Unione tipografico-editrice torinese (Latin text with parallel Italian translation); *L. Annaei Senecae Naturales quaestiones,* ed. Carmen Codoñer Merino (1979), Madrid: Consejo Superior de Investigaciones Científicas. See also Gross, Nikolaus (1989), *Senecas Naturales quaestiones: Komposition, naturphilosophische Aussagen und ihre Quellen*, Stuttgart: Steiner.

    Other ancient collections of questions include the Pseudo-Aristotelian *Problems*, Plutarch's *Symposiacs* and *Natural Questions*, Alexander's *Problems and Solutions*, Theophylact's *Natural Questions*, and the *Questions of Chosroes* attributed to Priscian of Lydia (6th C. AD), discussed by Pamela Huby, 'Questions and answers, problems and solutions in ancient thinking', paper presented to the conference 'Science Matters', University of Liverpool, July 1996, forthcoming in published proceedings of the conference (Oxford University Press).
86. There is much of interest in Plutarch's *Moralia*, available in many editions and translations. The text and translation of *Concerning the Face which appears in the Orb of the Moon*, ed. and trans. Harold Cherniss (1957), *Plutarch's Moralia* 12, Cambridge: Harvard University Press, London: William Heinemann, Loeb Classical Library, Harvard and London, has useful notes. See also Teodorsson, Sven-Tage (ed.) (1989–1996), *A Commentary on Plutarch's Table-Talk*, 3 vols, Göteborg: Acta Universitatis Gothoburgensis.
87. Modern historians have adopted their own terminology to distinguish the Platonism associated with the 'Old' Academy from 'Middle' Platonism. See chapter 2 of Dillon, John (1977), *The Middle Platonists: a Study of Platonism 80 BC to AD 220*, Ithaca, New York: Cornell University Press, and Barnes, Jonathan (1989), 'Antiochus of Ascalon', in Miriam Griffin and Jonathan Barnes (eds), *Philosophia Togata: Essays on Philosophy and Roman Society*, Oxford: Clarendon Press.
88. Dillon, John (1993), *Alcinous: The Handbook of Platonism*, Oxford: Clarendon Press, p. xl.
89. *Alcinous: The Handbook of Platonism*, trans. with an introduction and commentary by John Dillon (1993), Oxford: Clarendon Press; the work is also known as the *Didaskalikos*. Whittaker, J. (ed. and comm.) and Louis, Pierre (trans.), (1990), *Alcinoos, Enseignement des doctrines de Platon*, Les Belles Lettres, Paris: Budé.

See also Dillon, John (1977), *The Middle Platonists: 80 BC to AD 220*, Ithaca, New York: Cornell University Press.

90. Numenius of Apamea *Fragments*, ed. É. Des Places (1973), Paris: Les Belles Lettres.
91. On the Pythagoreans of this period see Thesleff, H. (1961), *An Introduction to the Pythagorean Writings of the Hellenistic Period*, Åbo: Academie; Thesleff, H. (ed.) (1965), *Pythagorica: the Pythagorean Texts of the Hellenistic Period*, Åbo: Academie; O'Meara, Dominic J. (1989), *Pythagoras Revived: Mathematics and Philosophy in late Antiquity*, Oxford: Clarendon Press.
92. For a useful, though somewhat dated, general history see Heath, T.L. (1921), *A History of Greek Mathematics*, 2 vols, Oxford: Clarendon Press, reprinted New York: Dover. See also Thomas, *Greek Mathematics* (see note 70), reviewed by O. Neugebauer (1943), *American Journal of Philology*, 64, 452–57.
93. Archytas, cited by Porphyry in his *Commentary on Ptolemy's Harmonics*, ed. J. Wallis (1699), *Opera mathematica*, Oxford, vol. 3, pp. 236–37, 1972 rpt. Hildesheim: Georg Olms Verlag; H. Diels, *Vorsokratiker*, 5th ed, vol. 1, pp. 431–32, both cited by Thomas (see note 70), vol. I, p. 5; see also Plato, *Republic*, Book 7, 530d. On Pythagoras and Pythagoreanism see Burkert (1972), *Lore and Science of Ancient Pythagoreanism* (see note 33).
94. Fowler (1987), *The Mathematics of Plato's Academy* (see note 47), p. 195; see also chapter 7.

    For examples of the variety of mathematical texts, see Chace, A.B. (1927–29), *The Rhind Mathematical Papyrus*, 2 vols, Oberlin, Ohio: Mathematical Association of America, and abridged reprint in 1 vol., Classics in Mathematics Education 8, Reston, Virginia: The National Council for Teachers of Mathematics, 1979; Tod, M.N. (1979), *Ancient Greek Numerical Systems: Six Studies*, Chicago: Ares, which reprints six articles on the epigraphical evidence for numerical systems, originally published in the *Annual of the British School at Athens* vols 18 (1911–12, pp. 98–132, 'The Greek numerical notation'), 28 (1926–27, pp. 141–57, 'Further notes on the Greek acrophonic numerals'), 37 (1936–37, pp. 236–58, 'The Greek acrophonic numerals'), 45 (1950, pp. 126–39, 'The alphabetic numeral system in Attica'), and 49 (1954, pp. 1–8, 'Letter-labels in Greek inscriptions') and 'Three Greek numerical systems', *Journal of Hellenic Studies* 33 (1913), pp. 27–34; Lang, M. (1956), 'Numerical notation on Greek vases', *Hesperia* 25, 1–24; Mau, J. and Müller, W. (1982), 'Mathematische Ostraka aus der Berliner Sammlung', *Archiv für Papyrusforschung*, 17, 1–10.
95. Plato *Republic*, Book 7, 525b–31e.
96. *Metaphysics* 1025b–26a. On Aristotle as a mathematician, see Heath, T.L. (1949), *Mathematics in Aristotle*, Oxford: Clarendon Press, reprinted New York: Garland, 1980.
97. Ptolemy Almagest 1.1. See also Taub, Liba Chaia (1993), *Ptolemy's Universe: the Natural Philosophical and Ethical Foundations of Ptolemy's Astronomy*, Chicago: Open Court.
98. Fowler (1987) (see note 47), p. 367.
99. See Fowler (1987) (see note 47), pp. 106–7, on Plato as a mathematician; in particular, he criticizes the views of Harold Cherniss (1945), *The Riddle of the Early Academy*, Berkeley: University of California Press; reprinted with an index by L. Tarán, New York and London: Garland, 1980.
100. Many of its propositions are used in the *Phaenomena* of Euclid, according to G. J. Toomer, 'Autolycus', in *OCD*, 3rd edn; see now Berggren, J.L. and Thomas, R.S.D. (1996), *Euclid's 'Phaenomena': a Translation and Study of a Hellenistic Treatise in Spherical Astronomy*, New York and London: Garland Publishing.
101. My account follows that of G.J. Toomer, 'Autolycus', in *OCD*, 3rd edn. Joseph

Mogenet (1950) has published a critical text of Autolycus' extant writings, Autolycus *[De sphaera quae movetur. De ortibus et occasibus.] Autolycus de Pitane: histoire du texte suivie de l'édition critique des traités de la sphère en mouvement et des levers et couchers*, Louvain: Université de Louvain, *Recueil de travaux d'histoire et de philologie* 3e sér., fasc. 37; a German translation has been published by Arthur Czwalina (1931), *Autolykos Rotierende Kugel und Aufgang und Untergang der Gestirne* (with *Theodosios von Tripolis Sphaerik in drei Büchern)*, Ostwalds Klassiker der exakten Wissenschaften 232, Leipzig: Akademische Verlagsgesellschaft. On the two versions of *Risings and Settings*, see Schmidt, Olaf (1952), 'Some critical remarks about Autolycus' *On Risings and Settings*', transactions of *Den 11te skandinaviske Matematikerkongress i Trondheim 22–25 August 1949*, 202–9.

102. Very little about Eudoxus' life and work is known with any certainty, not even his dates. Diogenes Laertius, in his biography of Eudoxus, reports that he was called 'Endoxus' ('illustrious') because of his brilliant reputation. Tantalizingly little is known about his relationships to such important contemporaries as his supposed teacher Archytas, Plato and Aristotle. Anecdotes relate his invention of a type of sundial, and his introduction of the practice of arranging furniture in a semi-circle to accommodate more people. See Taub, L. (1998), 'Eudoxus', in Edward Craig (ed.), *Routledge Encyclopedia of Philosophy*, London: Routledge.

See Lasserre, François (1966), *Die Fragmente des Eudoxos von Knidos*, Berlin: Walter de Gruyter & Co.; Sedley, David (1976), 'Epicurus and the Mathematicians of Cyzicus', *Cronache Ercolanesi*, 6, 23–54, on the physical models of Eudoxus' system. See also Lloyd, G.E.R. (1991), 'Saving the appearances', in *Methods and Problems in Greek Science*, Cambridge: Cambridge University Press, pp. 248–77; reprinted from *Classical Quarterly* 28 (1978), 202–22, on interpretations of Eudoxus' mathematical model.

103. Fowler (1987) (see note 47), p. 203.

104. Fowler (1987) (see note 47), p. 203. Surviving papyri fragments, described by Fowler, include material found at Oxyrhynchus, a large Graeco-Roman town, approximately 120 miles south of Cairo. See also Turner, E.G., Fowler, D.H., Koenen, L. and Youtie, L.C. (1985), 'Euclid, Elements I, Definitions 1–10 (P. Mich. iii 143)', *Yale Classical Studies*, 285, 13–24; Knorr, W. (1975), *The Evolution of the Euclidean Elements: a Study of the Theory of Incommensurable Magnitudes and its Significance for Early Greek Geometry*, Dordrecht: Reidel.

105. Euclid *Opera omnia*, ed. J.L. Heiberg, H. Menge and M. Curtze (1893–1916), 9 vols, Leipzig: Teubner; *Euclides Elementa*, ed. J.L. Heiberg, rev. E.S. Stamatis (1969–77), 5 vols in 6 parts, Leipzig: Teubner; Heath, T.L. (1926), *The Thirteen Books of Euclid's Elements*, 2nd edn, 3 vols, Cambridge: Cambridge University Press, reprinted New York: Dover, 1956. See also Knorr, W. (1989), *Textual Studies in Ancient and Mediaeval Geometry*, Boston; Itard, J. (1962), *Les Livres Arithmétiques d'Euclide*, Histoire de la pensée 10, Paris: Hermann.

On the *Sectio canonis: The Euclidean Division of the canon: Greek and Latin sources*: ed. and trans. André Barbera (1991), Lincoln: University of Nebraska Press, see Bowen, Alan C. (1991), 'Euclid's *Sectio canonis* and the history of Pythagoreanism', in Alan C. Bowen (ed.), *Science and Philosophy in Classical Greece*, New York and London: Garland Publishing, pp. 164–87. The *Sectio canonis* is variously attributed, for example, to Euclid or Porphyry.

106. Archimedes *Opera omnia cum commentariis Eutocii*, ed. J.L. Heiberg, 2nd edn, 3 vols, Leipzig: Teubner, 1910–15, reprinted Stuttgart: Teubner, 1972; vol. IV: *Archimedes Über einander berührende Kreise*, trans. Yvonne Dold-Samplonius, Heinrich Hermelink and Matthias Schramm (1975), Stuttgart: Teubner; *The Works of Archimedes edited in Modern Notation* (1897) with supplement, *The Method of*

Archimedes (1912), trans. T.L. Heath, Cambridge: Cambridge University Press, reprinted New York: Dover, n.d.; *Archimède: De la sphère et du cylindre, La mesure du cercle, Sur les conoïdes et les sphéroïdes*, vol. 1, ed. Charles Mugler (1970), Paris: Les Belles Lettres; *Archimède: Des spirales, De l'equilibre des figures planes, l'Arenaire, La quadrature de la parabole*, vol. 2, ed. Charles Mugler (1971), Paris: Les Belles Lettres; *Archimède: Des corps flottants, Stomachion, La méthode, Le livre des lemmes, Le problème des boeufs*, vol. 3, ed. Charles Mugler (1971), Paris: Les Belles Lettres; *Archimède: Commentaires d'Eutocius et fragments*, vol. 4, ed. Charles Mugler (1972), Paris: Les Belles Lettres; *Les Oeuvres complètes d'Archimède*, trans. Paul Ver Eecke (1921), Paris, Brussels: Desclée, de Brouwer; *Geometrical Solutions derived from Mechanics, a Treatise of Archimedes*, German trans. J.L. Heiberg, English trans. from German by Lydia G. Robinson (1942), La Salle, Ill.: Open Court, reprinted from *The Monist*, April 1909.

As Fowler (see note 47), p. 365, points out, Archimedes' isolation from the mathematicians of Alexandria is attested by the prefaces to his works.

107. On Strato of Lampsacus, see Wehrli, F. (1950), *Die Schule des Aristoteles: Texte und kommentar 5, Basel: B. Schwabe*; Gottschalk, H.B. (1965), *Strato of Lampsacus: some Texts, Proceedings of the Leeds Philosophical and Literary Society, Literary and Historical Section* XI, vi, 95–182.

108. Fragments of Hero's commentary survive in Abû'l 'Abbâs al-Fadl ibn Hatim ad-Nairîzî's (Anaritius) commentary on Euclid, *Anaritti in decem libros priores Elementorum Euclidis commentarii*, ed. M. Curtze (1899), *Euclidis Opera omnia supplementum*, Leipzig: Teubner.

109. Hero *Opera quae supersunt omnia* (1899–1914, reprinted 1976), 5 vols, Leipzig: Teubner; vol. I, *Pneumatica et automata*, ed. G. Schmidt; vol. II *Mechanica et catoptrica*, ed. L. Nix and W. Schmidt; vol. III *Rationes dimetiendi [=Metrica] et commentatio dioptrica*, ed. H. Schöne; vol. IV *Definitiones*, ed. J.L. Heiberg; vol. V., *Stereometrica, et de mensuris*, ed. J.L. Heiberg, Teubner; *Codex Constantinopolitanus palatii veteris* No. 1, ed. E.M. Bruins, 3 vols (vol. I Photographic reproduction of the manuscript; vol. II Greek transcription; vol. III Translation and commentary), Leiden: Brill, 1964. A re-edition of the principal manuscript of Hero's mathematical writings and sole source of the *Metrica* is the *Pneumatica*, trans. Joseph Gouge Greenwood, ed. Bennet Woodcroft (1851), introduced by Marie Boas Hall (1971), London: Macdonald & Co., New York: American Elsevier. See also the *Belopoietica*, trans. E. Marsden (1971), in *Greek and Roman Artillery: Technical Treatises*, Oxford: Clarendon Press; *Mechanica*, trans. A. Drachmann (1963), in *The Mechanical Technology of Greek and Roman Antiquity: a Study of the Literary Sources*, Munksgaard, *Acta historica scientiarum naturalium et medicinalium* 17. Concerning the works on practical measurement, see Toomer, G.J., 'Hero' *OCD*, 3rd edn.

110. *Aristarchus of Samos: the Ancient Copernicus*, ed. and trans. T.L. Heath (1913), Oxford: Clarendon Press, reprinted New York: Dover, 1981 (and many other reprints), includes the text, translation and commentary.

111. Apollonius of Perge *Conica*, Books I–IV, ed. J.L. Heiberg (1891, 1893, reprinted 1974) Cambridge, Book V, ed. L. Nix (1889), Stuttgart: Teubner; *Conics V–VII*, ed. and trans. G.T. Toomer (1990), 2 vols, New York: Springer, from Arabic text; Heath, T.L. (trans.) (1896, reprinted 1961), *Apollonius of Perga*; ver Eecke, P. (1923, reprinted 1963), *Les Coniques d'Apollonius de Perge*, all seven books, Paris: Blanchard; Czwalina, A. (1926), *Die Kegelschnitte des Apollonius*, first four books.

112. Aratus of Soli *Phaenomena*, ed. with translation and commentary, D. Kidd (1997), Cambridge: Cambridge University Press; trans. G.R. Mair, in *Callimachus Hymns and Epigrams, Lycophron, Aratus* (1921, reprinted), Cambridge: Harvard Uni-

versity Press, London: William Heinemann, Loeb Classical Library; see also Martin, J. (1956), *Histoire du texte des Phénomènes d'Aratos*, Paris.

113. Manilius, *Astronomica*, trans. G.P. Goold (1977), Cambridge, Massachusetts: Harvard University Press, London: William Heinemann, Loeb Classical Library; there are a number of other editions as well.

114. Geminus *Eisagoge eis ta phainomena (Elementa astronomiae)*, ed. and trans. Karl Manitius (1898), Leipzig: Teubner; *Introduction aux Phenomènes*, ed. G. Aujac (1975), Paris; *Gemini elementorum astronomiae capita I, III–VI, VIII–XVI, with a glossary*, ed. E. J. Dijksterhuis (1957), Leiden: E.J. Brill.

115. Fowler (1987) (see note 47), p. 9.

Diophantus *Opera Omnia cum Graecis Commentariis*, ed. P. Tannery (1893–95), 2 vols, Leipzig: Teubner; *Diophantus of Alexandria: a Study in the History of Greek Algebra*, ed. and trans. T.L. Heath (1910), 2nd edn, Cambridge: Cambridge University Press; *Books IV to VII of Diophantus' Arithmetica in the Arabic Translation attributed to Qusta ibn Luqu* , ed. and trans. Jacques Sesiano (1982), New York, Heidelberg: Springer; *Les arithmétiques, Livre IV*, ed. and trans. Roshdi Rashed (1984), Paris: Les Belles Lettres; *Les arithmétiques, Livres V, VI, VII*, ed. and trans. Roshdi Rashed (1984), Paris: Les Belles Lettres.

116. See Toomer, G.J., 'Diodorus (4) of Alexandria' in *OCD*, 3rd edn.

117. The astronomical work called the *Almagest* is also known by the latinized Greek title *Syntaxis mathematica*, ed. J.L. Heiberg (1898–1903), 2 vols, Leipzig: Teubner; modern translations include *Handbuch der Astronomie*, trans. K. Manitius, new edition corrected by O. Neugebauer, 2 vols, Leipzig: Teubner, 1963; *Ptolemy's Almagest*, trans. G.J. Toomer (1984), New York: Springer. Other astronomical writings may be found in *Opera astronomica minora*, ed. J.L. Heiberg (1907), Leipzig: Teubner; 'The Arabic version of Ptolemy's *Planetary Hypotheses*', ed. B.R. Goldstein (1967), in *Transactions of the American Philosophical Society*, n.s. 57, pt. 1, 3–55; *Tetrabiblos*, ed. F. Boll and A. Boer, Leipzig: Teubner, 1957; *Tetrabiblos*, ed. and trans. F.E. Robbins, Cambridge, Massachusetts: Harvard University Press, 1940, Loeb Classical Library. On music, *Die Harmonielehre des Klaudios Ptolemaios*, ed. Ingemar Düring, *Göteborgs Högskolas Arsskrift* 36, 1930) and *Harmonics*, trans. A. Barker (1989), in *Greek Musical Writings II*, Cambridge: Cambridge University Press; on optics, *L'optique de Claude Ptolémée dans la version latine d'après de l'émir Eugène de Sicile*, ed. A Lejeune, Louvain: Université de Louvain, *Recueil de travaux d'histoire et de philologie*, 4e série, fasc. 8, 1956; on geography, *Geographia*, ed. C.F.A. Nobbe, Hildesheim: Georg Olms, 1966, rpt of Leipzig 1843–45 edn. On a non-mathematical topic, see *Peri kriteriou*, the authorship of which is unclear, in *The Criterion of Truth: Essays written in Honour of George Kerferd together with a Text and Translation (with Annotations) of Ptolemy's On the Kriterion and Hegemonikon*, ed. Pamela Huby and Gordon Neal (1989), Liverpool: Liverpool University Press.

118. *Musici scriptores graeci*, ed. J. von Jan (1895), Leipzig: Teubner, reprinted Hildesheim: Olms, 1962.

119. Andrew Barker, *Greek Musical Writings* II (see note 117).

120. Aristotle *Meteorologica*, ed. and trans. H.D.P. Lee (1952, reprinted 1978), Cambridge: Harvard University Press, London: William Heinemann, Loeb Classical Library; *Meteorologica*, ed. E.W. Webster (1931), Oxford: Clarendon Press; *Theophrastus of Eresus On Winds and On Weather Signs*, translated, with an introduction and notes, and an appendix on the direction, number and nomenclature of the winds in classical and later times, ed. J.G. Wood and G.J. Symons (1894), London; *Theophrastus: Enquiry into Plants and Minor Works on Odours and Weather Signs*, trans. A. Hort (1916, reprinted 1961–68), 2 vols, Cambridge,

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121. For other geographical writers, see Müller, K. and Müller, T. (eds) (1848–1885), *Fragmenta historicorum graecorum*, 5 vols, Paris, Firmin Didot; Müller, K. (1885–61), *Geographi graeci minores*, 2 vols, Paris, Firmin Didot.
122. Iulius Firmicus Maternus *Mathesis*, ed. and trans. P. Monat (1992), Paris: Les Belles Lettres; *Iulii Firmici Materni Matheseos libri VIII*, ed. W. Kroll, F. Skutsch and K. Ziegler (1897–1913, reprinted 1968), 2 vols, Leipzig: Teubner; *Ancient Astrology: Theory and Practice: Matheseos libri VIII*, trans. J. Rhys Bram (1975), Park Ridge, New Jersey: Noyes Press; Dorotheus *Dorothei Sidonii carmen astrologicum*, ed. D. Pingree (1976), Leipzig: Teubner; Vettius Valens *Vettii Valentis Antiocheni anthologiarum libri novem*, ed. D. Pingree (1986), Leipzig: Teubner; *Vettius Valens d'Antioche, Anthologies, Livre I*, ed. Joelle-Frederique Bara (1989), Leiden: E.J. Brill; Hephaestio, *Hephaestio Thebanus Apotelesmatica*, ed. David Pingree (1973–74), 2 vols, Leipzig: Teubner.
123. Neugebauer, O. and van Hoesen, H.B. (eds) (1959), *Greek Horoscopes*, Philadelphia: American Philosophical Society; see also *Catalogus Codicum Astrologorum Graecorum* (=*CCAG*) (1898–1953), 12 vols, Brussels: Lamertin. The volumes are organized by place; the first section of each describes the astrological manuscripts, while editions of sections of the texts are to be found in the second part of the volume.
124. The literature related to medicine is covered in a separate bibliography, Thornton, John L. (1990), *Thornton's Medical Books, Libraries and Collections: a Study of Bibliography and the Book Trade in Relation to the Medical Sciences*, ed. Alain Besson, 3rd rev. edn, Aldershot: Gower.
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126. See also *Les Lapidaires Grecs*, ed. Robert Halleux and Jacques Schamp (1985), Paris: Les Belles Lettres.
127. The writings of Herodotus and Aristophanes are widely available in many editions and translations.
128. Beagon, Mary (1992), *Roman Nature: the Thought of Pliny the Elder*, Oxford: Clarendon Press; French, Roger (1994), *Ancient Natural History: Histories of Nature*, London and New York: Routledge; French, Roger and Greenaway, Frank (eds) (1986), *Science in the Early Roman Empire: Pliny the Elder, his Sources and Influence*, London: Croom Helm.
129. The Roman agricultural authors are available in the Loeb Classical Library series: *Marcus Porcius Cato On Agriculture, Marcus Terentius Varro On Agriculture*, trans. William Davis Hooper, rev. Harrison Boyd Ash (1935), Cambridge, Mass.: Harvard University Press, London: William Heinemann; *Columella de re rustica*, ed. and trans. Harrison Boyd Ash (1941), Cambridge, Mass.: Harvard University Press, London: William Heinemann; *Virgil Works*, trans. H. Ruston Fairclough (1978, rev. edn), 2 vols (vol. 1), Cambridge, Mass.: Harvard University Press, London: Heinemann. There are many other editions and translations of the *Georgics*, including that of John Dryden, which has been reprinted: *Virgil: The Georgics, with John Dryden's translation*, intro. Alistair Elliot (1981), Ashington.
130. Celsus *De medicina*, trans. W.G. Spencer (1935–38), 3 vols, Cambridge, Massachusetts: Harvard University Press, London: William Heinemann, Loeb Classical

Library; Aulus Cornelius Celsus, *De la médecene*, Tome 1: Livres 1–11, ed. Guy Serbat (1995), Paris: Les Belles Lettres.

131. Vitruvius *On Architecture*, ed. and trans. Frank Granger (1931), 2 vols, Cambridge, Mass.: Harvard University Press, London: William Heinemann, Loeb Classical Library.

132. Apuleius *De philosophia libri*, ed. C. Moreschini (1991), Stuttgart: Teubner; *Opuscules philosophiques et fragments*, ed. and trans. J. Beaujeu (1973), Paris: Les Belles Lettres. See also Bajoni, Maria Grazia (1994), 'Aspetti linguistici e letterari del "De mundo" di Apuleio', *Aufstieg und Niedergang der Römischen Welt* 34, 2, 1785–1832, on the translation attributed to Apuleius of the pseudo-Aristotelian *On the Cosmos*. The spurious *Herbarius* has been edited by Howald, E. and Sigerist, H.E. (1927), *Corpus Medicorum Latinorum* IV, Leipzig: Teubner.

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134. Alcinous *Didaskalikos* in *Platonis Dialogi secundum Thrasyli tetralogias dispositi*, ed. C.F. Hermann (1859), 6 vols in 3, Leipzig: Teubner; Alcinous, *The Handbook of Platonism*, trans. with an introduction and commentary by John Dillon (1993), Oxford: Clarendon Press. On some of the difficulties in identifying the author of the *Didaskalikos* see Whittaker, John (1987), 'Platonic philosophy in the Early Empire', *Aufstieg und Niedergang der Römischen Welt*, Teil II, Band 36, 1, 81–123.

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139. See Dzielska, Maria (1995), *Hypatia of Alexandria*, trans. F. Lyra, Cambridge, Massachusetts: Harvard University Press.

140. Neugebauer, O. (1975), *A History of Ancient Mathematical Astronomy* (=*HAMA*), 3 vols, Berlin & New York: Springer, vol. II, p. 959; Cleomedes, *Cleomidis caelestia (meteora)*, ed. Robert Todd (1990), Leipzig: Teubner; *De motu circulari corporum caelestium*, ed. and trans. Richard Goulet (1980), Paris: J. Vrin.

141. Eutocius' commentary on *Measurement of a Circle* is published in Archimedes, *Opera*, ed. J.L. Heiberg, vol. 3, 228–61. There are some problems with the dating of Eutocius; see 'Eutocius' in *DSB*.

142. Cameron, Alan (1990), 'Isidore of Miletus and Hypatia: on the editing of mathematical texts', *Greek, Roman and Byzantine Studies*, 31, 103–27. Regarding modernization of language, Cameron, p. 126, particularly points to Euctocius' discussion of a fragment of Archimedes. Professor Ineke Sluiter (personal communication) has pointed out that the practice of revising a mathematical text had parallels in literary scholarship; see Sluiter, Ineke (1998), 'Metatexts and the principle of charity', in Peter Schmitter and Marÿke, J. van der Wal (eds), *Metahistoriography: Theoretical and Methodological Aspects in the Historiography of Linguistics*, Münster: Nodus Publikationen, pp. 11–27 on other commentators, including Hipparchus.

143. Professor Ineke Sluiter (personal communication) mentions the modern example of *Gray's Anatomy*. See Law, Vivian and Sluiter, Ineke (eds) (1995), *Dionysius Thrax and the 'Techne grammatike'*, Münster: Nodus Publikationen.

144. See Toomer, G.J. (1984), 'Lost Greek mathematical works in the Arabic tradition', *Mathematical Intelligencer*, 6, 32–38.

145. These may have been been the products of discussions held with others; see Dodds, E.R., 'Plotinus', in *OCD*, 2nd edn.

146. Porphyry *(Life of Plotinus) ΠΟΡΦΥΡΙΟΥ ΠΕΡΙ ΤΟΥ ΠΛΩΤΙΝΟΥ ΒΙΟΥ ΚΑΙ ΤΗΣ ΤΑΞΕΩΣ ΤΩΝ ΒΙΒΛΙΩΝ ΑΥΤΟΥ (Porphyriou Peri tou Plotinou biou kai taxeos biblion autou)*, ed. Paul Kalligas (1991), Athens: *ΚΕΝΤΡΟΝ ΕΚΔΟΣΕΩΣ ΕΡΓΩΝ ΕΛΛΗΝΩΝ ΣΥΓΓΡΑΦΕΩΝ (Kentron Ekdoseos Ergon Hellenon Syngrapheon), ΑΚΑΔΗΜΙΑ ΑΘΗΝΩΝ ΒΙΒΛΙΟΘΗΚΗ Α. ΜΑΝΟΥΣΗ (Akademia Athenon Bibliotheke A. Manouse)* 1; *La vie de Plotin,* ed. and trans. Luc Brisson (1982–92), 2 vols, Paris: J. Vrin.

Plotinus *Plotini opera*, ed. Paul Henry and Hans-Rudolf Schwyzer (1964–82), 3 vols, Oxford: Clarendon Press; *Enneades*, ed. É. Bréhier (1924–38), 7 vols, Paris: Les Belles Lettres. *Plotinus*, trans. A.H. Armstrong (1966–88), 7 vols, Cambridge, Massachusetts: Harvard University Press; London: W. Heinemann, Loeb Classical Library (the Greek text is essentially that of P. Henry and H.R. Schwyzer); *The Enneads*, trans. Stephen MacKenna, rev. B.S. Page (1969, 4th edn), London: Faber (1991, Penguin edn, ed. J.M. Dillon, with some sections omitted); *The Essential Plotinus: Representative Treatises from the Enneads*, trans. Elmer O'Brien (1975), Indianapolis: Hackett; *Plotinus, Ennead III 6, On the Impassivity of the Bodiless*, trans. Barrie Fleet (1995), Oxford: Clarendon Press; New York: Oxford University Press.

See also Henry, P. (1938), *Les états du texte de Plotin*, Paris: Desclée de Brower et Cie.

147. See Dodds, E.R. 'Plotinus', in *OCD*, 2nd edn, citing a scholium to *Enneads* 4.4.30.
148. Bidez, Joseph (1913), *Vie de Porphyre le philosophe néoplatonicien*, Ghent and Leipzig: Librarie scientifique E. van Goethem and B.G. Teubner, Université de Gand, Recueil de travaux publiés par la Faculté de Philosophie et Lettres 43, p. iv.
149. *Porphyrios Kommentar zur Harmonielehre des Ptolemaios*, ed. I. Düring (1932), Göteborg, New York (1980 reprint); Alexanderson, Bengt (1969), *Textual Remarks on Ptolemy's 'Harmonica' and Porphyry's 'Commentary'*, Göteborg: Studia Graeca et Latina Gothoburgensia 27.
150. [Porphyry] *Pros Gauron*, ed. Karl Kalbfleisch (1895), 'Die neuplatonische, fälschlich dem Galen zugeschriebene Schrift Πρὸς °αῦρον εpὶ τοῦ ὧς ἐμψυχοῦται τὰ ἐμβρυα', *Abhandlungen der Königlichen Akademie der Wissenschaften zu Berlin*, Anhang: 1–80; French trans. and comm. A.-J. Festugière, *La Révelation d'Hermès* (1944–54), vol. iii, Paris.
151. Angelo Raffaele Sodano (1974), *Porfirio: I frammenti dei commentari al Timeo di Platone*, Naples: Centro Bibliotecario.
152. Porphyry *Porphyrii philosophi Platonici opuscula selecta*, ed. August Nauck (1886), Leipzig: Teubner, reprinted Hildesheim: Olms, 1963; *Porphyrii philosophi fragmenta*, ed. Andrew Smith and David Wasserstein (1993), Stuttgart: Teubner; Romano, Francesco (1985), *Porfirio e la fisica aristotelica* (in appendice la traduzione dei frammenti e delle testimonianze del 'Commentario alla fisica'), Catania: Università di Catania, Symbolon 3; *Select works of Porphyry*, trans. Thomas Taylor [1758–1835] (1994), Frome: Prometheus Trust; *Vie de Pythagore; Lettre à Marcella,* ed. Edouard des Places, with appendix by A.-Ph. Segonds (1982) Paris: Les Belles Lettres; *De abstinentia* (*De l'abstinence*), ed. and trans. Michel Patillon and Alain Ph. Segonds, with Luc Brisson (1995), Paris: Les Belles Lettres.
153. Iamblichus *De mysteriis*, ed. Edouard De Places (1966), Paris: Budé; *Iamblichi In Nicomachi Arithmeticam introductionem liber*, ed. Ulrich Klein (1975), Stuttgart: Teubner, 1975 reprint, with corrections to 1894 Leipzig edn by Ermenegildo Pistelli; *Protrepticus* [*The exhortation to philosophy*], (including the letters of Iamblichus and Proclus' commentary on the Chaldean oracles) trans. Thomas Moore Johnson, ed. Stephen Neuville (1988), Grand Rapids, Michigan: Phanes Press; *Protreptique*, ed. and trans. Edouard Des Places (1989), Paris: Les Belles Lettres; [*Protrepticus*] *Aufruf zur Philosophie Iamblichos*, trans. Otto Schönberger (1984), Würzburg: Königshausen und Neumann; *The Theology of Arithmetic: on the mystical, mathematical and cosmological symbolism of the first ten numbers, attributed to Iamblichus* (the authorship of this work is disputed), trans. Robin Waterfield (1988), Grand Rapids, Michigan: Phanes Press; *On the Pythagorean Life*, trans. Gillian Clark (1989), Liverpool: Liverpool University Press; *On the Pythagorean Way of Life*, ed. and trans. John Dillon and Jackson Hershbell (1991), Atlanta, Georgia: Scholars Press.
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157. Proclus *A Commentary on the First Book of Euclid's Elements*, trans. G.R. Morrow, Princeton: Princeton University Press, 1970. *Commentaire sur la République*, trans. A.J. Festugière (1970), 3 vols, Paris: Vrin. *In primum Euclidis Elementorum commentarii*, ed. G. Friedlein (1873), Leipzig: Teubner. *In Platonis Rem publicam commentarii*, ed. W. Kroll (1899–1901), 2 vols, Leipzig: Teubner; *Institutio physica* (*Elements of Physics*), ed. and trans. A. Ritzenfeld (1912), Leipzig: Teubner; *Procli Diadochi Hypotyposis astronomicarum positionum* (*Outline of Astronomical Theories*), ed. and trans. K. Manitius (1909), Leipzig: Teubner; *Procli Diadochi in Platonis Timaeum commentaria*, ed. E. Diehl (1903–6), 3 vols in 2, Leipzig: Teubner. See Siorvanes, L. (1996), *Proclus: Neo-Platonic Philosophy and Science*, Edinburgh: Edinburgh University Press.
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159. For the text of Philoponus' commentaries on Aristotle, see CAG vols 13–17. vol.13 pt. 1: *Philoponi (olim Ammonii) in Aristotelis Categorias commentarium*, ed. Adolfus Busse (1898), Berlin: Georg Reimer; vol. 13 pt. 2: *Ioannis Philoponi in Aristotelis Analytica Priora commentaria*, ed. Maximilianus Wallies (1905), Berlin: Georg Reimer; vol. 13 pt. 3: *Philoponi in Aristotelis Analytica Posteriora cum Anonymo in librum II*, ed. Maximilianus Wallies (1909), Berlin: Georg Reimer; vol. 14 pt. 1: *Ioannis Philoponi in Aristotelis Meteorologicorum librum primum commentarium*, ed. Michael Hayduck (1901), Berlin: Georg Reimer; vol. 14 pt. 2: *Ioannis Philoponi in Aristotelis libros de Generatione et Corruptione commentaria*, ed. Hieronymus Vitelli (1897), Berlin: Georg Reimer; vol. 14 pt.3: *Ioannis Philoponi (Michaelis Ephesii) in libros de Generatione Animalium commentaria*, ed. Michael Hayduck (1903), Berlin: Georg Reimer vol. 15: *Ioannis Philoponi in Aristotelis de Anima libros commentaria*, ed. Michael Hayduck

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ΙΩΑΝΝΟΥ ΓΡΑΜΜΑΤΙΚΟΥ ΑΛΕΞΑΝΔΡΕΩΣ (ΤΟΥ ΦΙΛΟΠΟΝΟΥ) ΕΙΣ ΤΟ ΠΡΩΤΟΝ ΤΗΣ ΝΙΚΟΜΑΧΟΥ ΑΡΙΘΜΗΤΙΚΗΣ ΕΙΣΑΓΩΓΗΣ (Ioannou grammatikou Alexandreos (tou Philoponou) eis to proton tes Nikomachou arithmetikes eisagoges), ed. Richard Hoche (1864), Leipzig: Teubner; *[De usu astrolabii] Traité de l'astrolabe*, reprinted ed. K.B. Hase with trans. A.P. Segonds (1981), Paris: Société internationale de l'astrolabe.

See also Sorabji, R. (ed.) (1987), *Philoponus and the Rejection of Aristotelian Science*, London: Duckworth.

160. Sorabji, Richard (ed.) (1990), *Aristotle Transformed*, p. 13; see also Sorabji, Richard (1987), 'John Philoponus', in R. Sorabji (ed.), *Philoponus and the Rejection of Aristotelian Science.*

161. Rudio, Ferdinand (1907), *Der Bericht des Simplicius über die Quadraturen des Antiphon und des Hippokrates*, Leipzig: Teubner, Urkunden zur Geschichte der Mathematik im Altertume 1. Also see Hadot, Ilsetraut (1990), 'The life and work of Simplicius in Greek and Arabic sources', in R. Sorabji (ed.), *Aristotle Transformed*, pp. 275–303; it should be noted that the attribution of the commentary covering *On the soul* is not entirely certain. For the text of Simplicius' commentaries on Aristotle, see *CAG* vols 7–11. Vol. 7: *Simplicii in Aristotelis de Caelo commentaria*, ed. J.L. Heiberg (1894), Berlin: Georg Reimer. Vol. 8: *Simplicii in Aristotelis Categorias commentarium*, ed. Carolus Kalbfleisch (1907), Berlin: Georg Reimer. Vol. 9: *Simplicii in Aristotelis Physicorum libros quattuor priores commentaria*, ed. Hermann Diels (1882), Berlin: Georg Reimer. Vol. 10: *Simplicii in Aristotelis Physicorum libros quattuor posteriores commentaria*, ed. Hermann Diels (1895), Berlin: Georg Reimer. Vol. 11: *Simplicii in libros Aristotelis de Anima commentaria*, ed. Michael Hayduck (1882), Berlin: Georg Reimer.

(In Aristotelis Physicorum libros commentaria. Pars 6.) Simplicius on Aristotle's Physics 6, trans. David Konstan (1989), Ithaca, New York: Cornell University Press; *Simplicius on Aristotle's Physics 7*, translated by Charles Hagen (1994), London: Duckworth; *(In Aristotelis Physicorum libros quattuor priores commentaria.) Corollaries on Place and Time*, trans. J.O. Urmson, notes by Lucas Siorvanes (1992), London: Duckworth; *(In Aristotelis Physicorum libros quattuor priores commentaria.) On Aristotle Physics 4.1–5, 10–14*, trans. J.O. Urmson (1992), London: Duckworth; *In Aristotelis Categorias. Commentaire sur les Catégories*, trans. Ilsetraut Hadot (1990), Leiden: E.J. Brill.

In Aristotelis Physicorum libros commentaria Philoponus Corollaries on Place and Void (with) *Simplicius Against Philoponus on the Eternity of the World*, trans. David Furley and Christian Wildberg (1991), London: Duckworth.

162. Gätje, H. (1982), 'Simplikios in der arabischen Überlieferung', *Der Islam*, 59, 16; Sabra, A.I. (1969), 'Simplicius' proof of Euclid's parallel postulate', *Journal of the Warburg and Courtauld Institutes*, 32, 1–24.

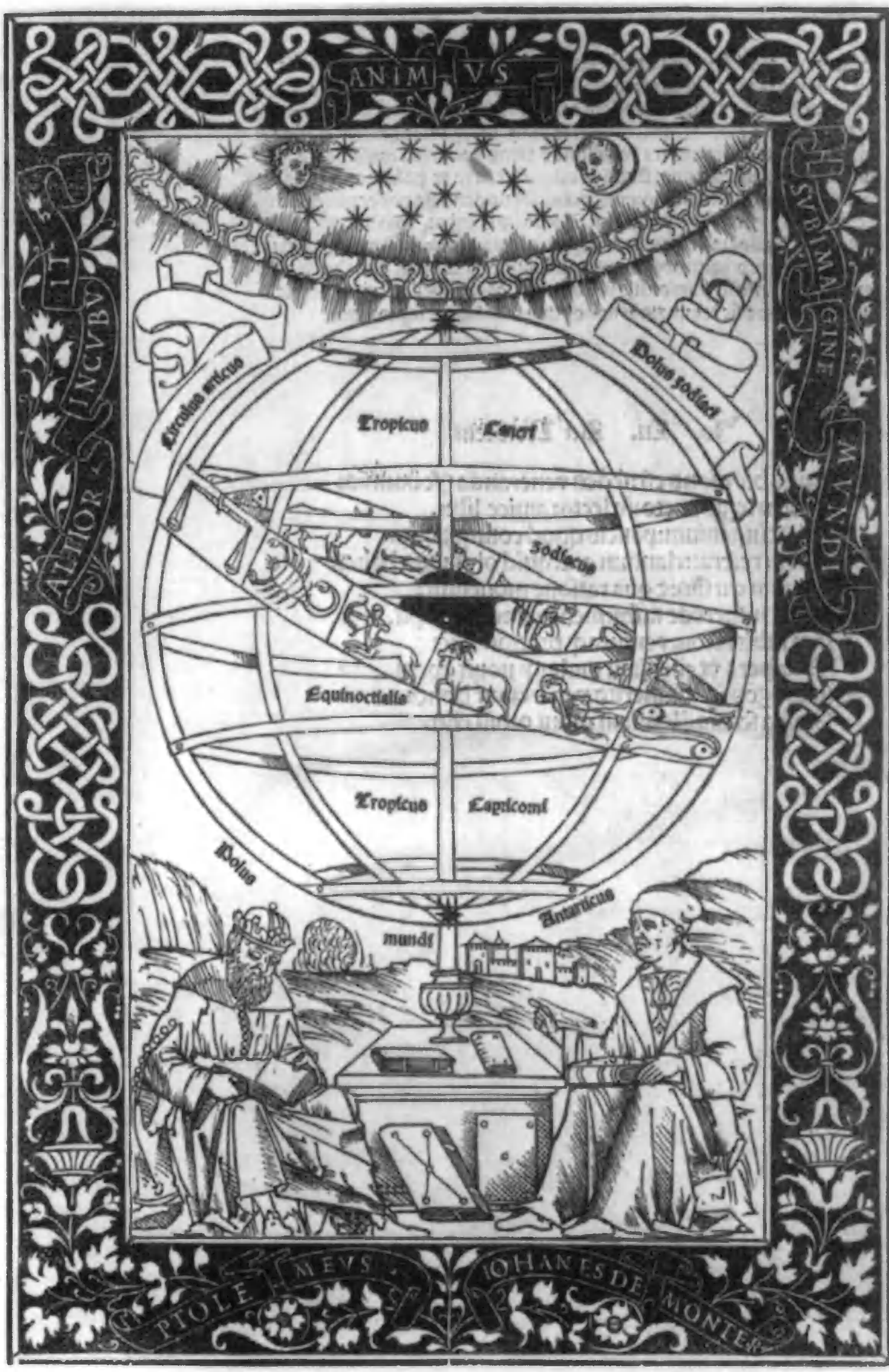
Chapter Three

Transitions 1: Scientific Writing in the Latin Middle Ages

Steven J. Livesey

A survey of scientific writing produced during the Latin Middle Ages is indeed a daunting task, for beyond the length of the period under investigation and the variety of the cultural settings and influences, medieval writers produced an astonishing variety of works that can under most definitions be construed as scientific in character. As a result, this section will not attempt to survey comprehensively the achievements of all such authors in the Middle Ages, or even the canon of 'celebrated' figures in medieval science. Rather, the goal will be to assess the various styles of scientific writing, with examples drawn from medieval works. The notes and bibliography are intended to provide initial sources for investigating the literary output of many of these authors, both individually and collectively, and to provide materials that assist in a better understanding of the cultural foundation for medieval scientific writing.

While the period between the fifth and the tenth centuries produced little in the way of scientific achievement, it is customary to begin an investigation of the Western Middle Ages with a handful of authors who at the same time inherited the late-ancient encyclopaedic tradition, preserved ancient materials and adapted and moulded them, often in the service of the Church. Boethius (480–524), for example, translated several of Aristotle's logical works (which became known as the *Ars vetus* in the Middle Ages), Euclid's *Elements* and Porphyry's *Isagoge*. In addition, Boethius also compiled handbooks on ancient sciences, including arithmetic and music, that became standard texts in the early Middle Ages. But apart from these strictly scientific texts, he also composed the enormously popular *De consolatione philosophiae* and several theological trea-



1. Regiomontanus, *Epytoma in Almagestum Ptolomei* (1496).
Reproduced courtesy of Bernard Quaritch Ltd.

tises which served as transmitters of scientific issues and later became the objects of commentary traditions.[1]

Similar developments can be seen in the works of Martianus Capella (fl. 410–439), whose *De nuptiis philologiae et mercurii* transmitted ancient materials on the seven liberal arts;[2] Cassiodorus Senator (c. 480–c. 575), whose *Institutiones* served as a scientific as well as theological encyclopedia and textbook for the monastic communities of the early middle ages;[3] Isidore of Seville (c. 560–636), whose *Etymologies* and *De natura rerum* preserved ancient materials often in inconsistent forms;[4] and the Venerable Bede (d. 735), whose *De natura rerum* (based on Isidore and Pliny) and *De temporibus* were produced in large part for the practical functions of the Church.[5] Such authors were keenly aware of the loss of considerable ancient material and the fragility of their sources; among the motivations for their activities was the preservation and consolidation of such materials, together with a continuation of late ancient ideals of virtue (now transformed under Christian sensibilities).

Gerbert (later Pope Sylvester II) (c. 945–1003) is an important transitional figure at the end of the tenth century. Scholasticus at Reims, and subsequently abbot at Bobbio, archbishop of Reims and Ravenna, and finally pope, Gerbert combined intellectual curiosity with political ambition. The author of at least one logical treatise and perhaps a treatise on the astrolabe, Gerbert's pivotal role can also be seen in his extensive correspondence, in which he solicited or announced translations from Arabic texts or discoveries of earlier Latin traditions. His attainment of significant positions within the Church, together with personal attachments to patrons (principally the Saxon emperor Otto III) help to explain his influence on later developments.[6]

While increased acquaintance with ancient Greek and Arabic scientific texts had already begun in the tenth century, the translation movement accelerated in the twelfth century and continued well into the thirteenth century and in some quarters even into the fourteenth century. By its conclusion, the full range of philosophical and scientific literature had been translated into Latin, often directly from the Greek, on other occasions through Arabic and other intermediate translations and accompanied by commentary literature from the Islamic world. While a full survey of the translation movement cannot be undertaken here,[7] some of the more significant translators and their works deserve to be mentioned.

Among the translators from Greek to Latin, one of the most influential was the canonist James of Venice (d. post 1147), whose translations of Aristotle's work, including the *Physics*, *Metaphysics*, *Posterior Analytics*, *Parva naturalia*, the *Sophistici elenchi* and probably the *Prior Analytics*, and Alexander of Aphrodisias' commentary on the *Posterior Analytics* often were among the first new translations of Aristotle known in Europe and came to be regarded as standard editions of these works. James is also reported to have written commentaries on Aristotle's works, including the *Sophistici elenchi* and the *Posterior Analytics*.[8]

The Flemish Dominican, William of Moerbeke (d. 1286), translated or retranslated several of Aristotle's works, including parts of the *Metaphysics*, *Meteorology*, *De caelo*, *De motu animalium*, *De progressu animalium*, *Historia animalium* and *De partibus animalium*, and revised earlier translations of many works, including the *Sophistici elenchi*, *Posterior Analytics*, *Physics* and *Metaphysics*. In addition, he translated several Greek commentaries on Aristotle, as well as works of Proclus, Alexander of Aphrodisias, Archimedes, and Ptolemy. A partial testimony to his influence in these areas can be seen in the hundreds of manuscripts and scores of editions in which they survive, from the late thirteenth century well into the early modern period.[9]

Gerard of Cremona (c. 1114–87) is credited with scores of translations from Arabic to Latin in fields spanning logic, mathematics, optics, astronomy, philosophy and medicine. These include several of Aristotle's works (the *Posterior Analytics*, *Physics*, *De caelo*, *De generatione et corruptione* and others), the *Almagest*, Euclid's *Elements*, al-Khwārizmī's *Algebra*, al-Kindī's *De aspectibus* and Thābit ibn Qurra's *De motu octave spere*.[10] By Gerard's time, the Iberian peninsula had already become a favourite site for translators, including John of Seville (fl. 1133–42) whose translations included al-Farghānī's *De scientia astrorum* and Qusṭā ibn Lūqā's *De differentia spiritus et anima*,[11] Robert of Chester (fl. 1141–50), who translated al-Khwārizmī's *Algebra*, Robert of Ketton (d. post 1157), who translated al-Kindī's *De iudiciis astrorum*,[12] and Hermann the Dalmatian (fl. 1138–54), whose translations included Ptolemy's *Planisphere*, Abū Ma'shar's *Great Introduction to the Science of Astrology* and the *Elements*.[13]

Unlike most of the other translators from Arabic to Latin, Adelard of Bath (fl. 1116–42) seems not to have travelled in Spain. After studies at Tours and a period of teaching at Laon, Adelard travelled for seven years, with stops in Salerno, Sicily, Cilicia, Syria and perhaps Palestine. His translations include perhaps the first complete translation of Euclid's *Elements*, as well as Abū Ma'shar's *Shorter Introduction to Astronomy* and al-Khwārizmī's *Astronomical Tables*. Although he also was the author of two philosophical works [*De eodem et diverso* and *Quaestiones naturales*] and treatises on the astrolabe and on falcons, his primary significance rests on the early translations of ancient and Islamic texts.[14]

A complete account of the translation movement would include discussions of Burgundio of Pisa (fl. 1136–93), Plato of Tivoli (fl. 1132–46), Michael Scot (fl. 1217–35), and Henricus Aristippus (fl. 1156–62) among others, but these samples suffice to show that interest in the translation movement was not confined to a single region: the translators converged on the Iberian peninsula, Italy or Byzantium from across Europe. In working with both Arabic and Greek texts, the translators often preferred a literal conversion of the material, making those (like Hugh of Santalla, fl. 1145) who favoured translations *ad sensum* somewhat unusual (although, of course even Latin translations, like those of Gerard of Cremona, who adhered strictly to the Arabic text, might vary dra-

matically from the Greek original because the earlier intermediary had resulted from a more liberal technique). Nor was there considerable organization in the translation movement: the frequent duplication of translations, sometimes occasioned by dissatisfaction with previous attempts, more often resulted from ignorance of earlier work. And finally, as Mlle d'Alverny suggested, the rather significant geographical diversity among the translators and their common itinerant tendencies may have helped to diffuse the translations among the major *studia* of Europe.[15]

Having inherited this rich store of texts, European scholars now were faced with the problem of interpreting and assimilating them.[16] In contrast to the often assertoric nature of early medieval handbooks of science,[17] the new literature beginning in the twelfth century adopted a more aggressive and argumentative approach to the text. Over the past century, we have come to recognize significant stages within this development, both in the intellectual content of the arguments and the physical format of the texts themselves.

Early commentators often glossed the text, in much the same way that glosses on the Bible had long been a form of explicating an authoritative source. Many surviving copies of the Latin translations, catalogued by the editors of the *Aristoteles latinus* series,[18] contain glosses on the text that demonstrate a growing sophistication in assimilating Aristotle. In the twelfth century, Peter Abelard (1079–1142) glossed the whole of the *Ars vetus*, and his sometime adversary, William of Champeaux (c. 1070–1122) did the same for the *Perihermenias*. In the early thirteenth century, the English scholar Alfredus de Sareshel composed glosses on the *Meteorologies* and the pseudo-Aristotelian *De plantis*, the latter gloss surviving in some twenty manuscript copies. Here the explanation of the text closely followed the original plan of the work and sought to clarify obscure or at least unfamiliar details within the text. At the same time, literal commentaries – often extensions of the glossed page – provided somewhat more elaborate explanations, but seldom departed extensively from the text. As many scholars have noted, and indeed as he himself observed, the literal commentaries on Aristotle made by Albert the Great (c. 1200–80) were intended as a *vade mecum* for students within the Dominican Order who faced a bewildering array of new scientific books; the focus in such cases was Aristotle, not the original speculations of the commentator.[19]

Parallel with these developments were techniques that medieval writers referred to as *ordinatio* and *compilatio*.[20] The onslaught of new materials was so great in the twelfth and early thirteenth centuries that medieval writers sought to provide mechanisms for getting readers into the material as expeditiously as possible, to arrive at the *auctoritates*, or ideas of the author. *Ordinationes*, or systematic indications of the order within a text, came to be adopted both as a way of reading, and later as a means of teaching the text. Rubrics at the head of chapters, as well as subdivisions within chapters, often visually distinguished from the rest of the text by colour or symbol, were provided as aids for assimilation. Often these early divisions of texts became permanent standards

within the textual tradition: the divisions of Aristotle's text adopted by Averroes, for example, provided a uniform means of referring to the text even in the absence of the Commentator's work.

However useful these techniques proved in easing the reader into the text, the text remained as voluminous as ever. The next step proved to be *compilatio*, in which a new *ordinatio* was imposed by rearranging the text and combining it with other materials. Its zenith can be seen in the work of Vincent of Beauvais (c. 1190–c. 1264). His *Speculum maius*, or 'great mirror', is composed of three parts, the *Speculum naturale*, *Speculum historiale*, and *Speculum doctrinale*, in which Vincent surveyed created nature, human history and the learned arts, respectively. The *Speculum naturale* follows the order of the six days of creation: under the creation of light, he includes 34 chapters on optics; in books 3 and 4, on the second day of creation, he discusses the sciences of astronomy and meteorology; the third day lends itself to a discussion of geology and mineralogy; in the fourth and fifth days, he includes 171 chapters on herbs, 134 on seeds and grains, 161 on birds, and 46 on fish. As a whole, the *Speculum maius* comprises 80 books and 9885 chapters, an enormous compilation that draws upon translated Greek and Arabic sources, as well as derivative Latin materials. Vincent insists that there is little of his own creation to be found in the work; his contribution is the new *ordo* that brings authoritative texts to bear on the subject matter. In its constituent parts, the *Speculum* underwent 15 editions before 1500 and survives in approximately 400 manuscript copies, testimony to its enormous influence in the Middle Ages and beyond.[21] Many of the same conclusions, about both the structure and subsequent influence of their works, may be made for Bartholomew Anglicus' *De proprietatibus rerum* (c. 1240)[22] and Brunetto Latini's *Li livres dou trésor* (c. 1265).[23]

While these particular compilations were seldom the subject of scholastic curricula in universities, many of the techniques of *ordinatio* and *compilatio* were transferred to the schools. The medieval curriculum comprised a broad array of works, especially in the faculty of arts, that included Islamic sources (especially the works of Avicenna and Averroes), ancient sources beyond the works of Aristotle, and of course the extensive body of Aristotle's texts. The latter cannot be emphasized too strongly, for Aristotle provided medieval scholars with a comprehensive framework of study, a common vocabulary of science, the very notion of science as an organized body of knowledge, and the extensive content for many of those sciences. And while in the early thirteenth century Aristotle's positions were modified by the influx of non-Aristotelian sources (Avicenna and the pseudo-Aristotelian *Liber de causis* being the most prominent), Aristotle's role also received assistance from the extensive commentaries of Averroes.

The Latin versions of Avicenna's *Kitāb al-Shifā*, which covered Aristotle's logical works, physics and metaphysics, with an intermediate section on mathematics, were made in Spain shortly after 1150. By the early thirteenth century, they were being read in schools in the north, and some have suggested that their

popularity, along with other contributing factors, may have combined to slow the reception of Aristotle's works at the University of Paris.[24] Certainly his tendency to combine to some degree readings of Plato with those of Aristotle served to influence Western interpretations of Aristotelian positions.[25] Latin Avicenna studies received enormous assistance from the labours of Mlle D'Alverny, who published a comprehensive list of manuscripts containing Latin translations of Avicenna's texts[26] that became the foundation of continuing publications of critical editions.[27]

The Latin versions of Averroes' commentaries on Aristotle were vitally important because of their comprehensive coverage of the Philosopher's works and their rather different perspective on those texts, one that bears a strong mark of the Islamic philosophical context in which the commentaries were written. The Latin translations of seventeen of Averroes' works were in use beginning in the 1230s, and the rather significant number of surviving manuscripts, together with the frequent references to them in scholastic texts emphasize the central importance of the Commentator's position in the later Middle Ages.[28] Some readers, like Roger Bacon (1214?–94), rejected Averroes' positions because they considered them corruptions of Aristotle;[29] as one may see from the Condemnations of 1270 and 1277, others criticized the anti-Christian implications of some Averroist positions.[30] But still others, like Siger of Brabant (c. 1240–84) and Boethius of Dacia (fl. 1270) in the thirteenth century, John of Jandun (1285/89–1328) in the fourteenth, or Paul of Venice (1369–1429) in the fifteenth, were intrigued by his interpretation of Aristotle. Modern scholars have come to refer to them as the Latin Averroists, whose significance extends from discussions about the nature and methodology of science, to issues of medical theory and practice, and finally to the relationship between theology and science.[31]

One of the most interesting bridges between Islamic and Christian culture is the Catalan scholar, Ramón Lull (c. 1232–1316). The son of wealthy parents in Majorca, Lull was converted to a religious life at the age of 30, then set out in turn to convert Muslims to Christianity. So great was Lull's interest in Islam that his own scholarship employs, in the view of one modern scholar, the dialectic of the Kalām. In his prolific writings (of his nearly 300 works, some 250 survive), a frequent theme is the analysis of God through nine absolute principles or dignities. His *Ars compendiosa* manipulated these principles in a combinatory way thereby drawing on similar currents in Muslim and Jewish theology and alleviating linguistic barriers while developing an algebraic logic. This method was, in turn, applied to other sciences, as for example in *The Tree of Science* (1296).[32]

Of course, the primary focus of attention was Aristotle himself. As glosses became more elaborate, they constituted proto-commentaries on the text that eventually acquired lives of their own, first as literal commentaries on the text, and eventually as *quaestiones* focused on significant aspects of Aristotle's positions. There are at present some 850 medieval commentators known to have produced written commentaries on Aristotle's texts; the total number of genuine

or arguably genuine commentaries (either extant or attested in historical documents) is approximately 2500.[33] But of these 850 commentators, slightly more than 600 produced only one or two commentaries. On the other hand, fewer than 50 produced at least 10 works. While the exigencies of textual survival and the frailty of the historical record are surely at work here, these numbers indicate in some measure the disparities between the more productive masters in medieval universities and other more modest achievements.

One of the earliest and most influential attempts to come to terms with Aristotle's material can be found in the works of Robert Grosseteste (d. 1253). Although he was not a member of the Order, he became the first lector to the Franciscan studium at Oxford, and thereby exercised considerable influence over the subsequent thought of Franciscans at Oxford and elsewhere. His commentary on the *Posterior Analytics* both explained and extended the Philosopher's discussion of method, and was cited subsequently almost as frequently as Aristotle himself. His commentaries on Aristotle's natural philosophical works, including the *Physics*, his works on light, and his *Hexameron* display the confluence of Aristotelian and non-Aristotelian influences, including Platonism and Neoplatonism.[34]

Heading the list of commentators on Aristotle is the Parisian master, Jean Buridan (d. c. 1358). Rising from a rather humble background, Buridan passed through the ranks of the Arts Faculty, becoming not only master of arts at Paris, but eventually rector of the University at the moment of a celebrated controversy with his colleague, Nicolaus of Autrecourt (d. p. 1350). His commentaries on Aristotle focused on the *Physics*, *De anima*, *Metaphysics*, *De caelo*, *Politics* and *Nicomachean Ethics*, together with extensive commentaries on the logical works. Buridan is often cited for his extensive use of impetus as a causal agent in the natural world: in his commentary on the *Physics*, for example, impetus both sustains projectile motion and explains the acceleration of a body undergoing natural motion. In the same passage, impetus is cited as a quasi-permanent quality conferred on celestial bodies at the moment of creation, one that is sufficient to explain continued motion in the absence of resistance in the heavens.[35]

Buridan's physical and cosmological positions were modified or extended by his students, Albert of Saxony (c. 1316–90),[36] Marsilius of Inghen (c. 1330/40–96)[37] and Nicole Oresme (d. 1382). Oresme in particular expanded upon Buridan's discussions of relative motion in *De caelo*, in which the possibility of terrestrial motion was raised but eventually denied, again for reasons of impetus. Oresme, by contrast, showed how observational, theoretical and theological objections to terrestrial motion might be answered; yet, like Buridan, he remained convinced of the stability of the earth.[38]

While impetus was treated most elegantly by Buridan and Oresme, this was not the first citation of the theory. Beginning with Anneliese Maier, scholars have assumed that the first extended and affirming discussion of impetus was found not in a commentary on the *Physics*, but rather in the 1319–20 lectures on a theological work, Peter Lombard's *Sentences*, made at Paris by Franciscus

de Marchia (d. p. 1344).[39] Maier and others observed that in contrast to Aquinas and Roger Bacon, who argued against impetus as a causal mechanism for projectile motion, de Marchia embraced it and applied it equally to the sacrament of the eucharist and physical motion. But recently it has been discovered that a still earlier adoption of impetus can be found in the Franciscan commentator on the *Physics*, Richard Rufus of Cornwall (d. p. 1259),[40] whose position Bacon seems to have criticized.

Two other areas of physical theory deserve attention. One corresponds to the modern field of dynamics, or as medieval scholars referred to it, *motus quoad causam*. One of the chief architects of late medieval developments in this field was Thomas Bradwardine (d. 1349), originally a fellow at Merton College, Oxford, and later Archbishop of Canterbury. In his *De proportionibus motuum*, Bradwardine surveyed various thirteenth-century positions on the factors involved in motion before arguing his own position regarding the relationship between the moving cause, resistance to motion, and the resulting speed of the object. Bradwardine's text quickly became a widely used source, either in its complete form, or in various versions known as *Proportiones breves* that were required in fourteenth- and fifteenth-century university curricula. Bradwardine was also the author of a widely used *Geometria speculativa* that provided among other things assistance to readers of Aristotle's mathematical examples.[41]

The other area of physical theory concerns the work of the so-called Oxford Calculators and their followers. In the 1330s and 1340s, a group of scholars often associated with Merton College, but actually reflecting somewhat wider institutional ties – William Heytesbury (d. 1372/73), John Dumbleton (d. 1349), and Richard Swineshead (fl. 1340–55) among others – were concerned with the ways by which qualities were extended, either spatially or temporally, in substances. Heytesbury's *Regule solvendi sophismata* and Swineshead's *Liber calculationum* focused on the 'latitude of forms', and many of their positions spread quickly to the Continent, so that by about the mid-century Oresme produced his own version, now given geometrical foundations and referred to as 'configurations'. Many of the works of the Oxford Calculators and their Parisian counterparts were transmitted widely beginning in the second half of the fourteenth century, and eventually received broad circulation in Italian incunable editions.[42]

Although its role has not received the same attention as that of its counterpart in the early modern period, the medieval espistolary tradition conveyed some interesting scientific products, the most notable of which was Peter Peregrinus' description of the lodestone. Written in 1269 while he was on campaign in southern Italy under Charles of Anjou, Peter's *Epistola de magnete* recounts the properties of the lodestone and their causes, as well as techniques for constructing compasses and, less successfully, a perpetual motion machine.[43]

Within the tradition of the exact sciences, Boethius produced, as we have seen, texts on the quadrivial subjects, of which his *De institutione musica* and *De institutione arithmetica* continued as standard texts for young arts students. But a variety of newer texts by later medieval authors also found their way into

the university curriculum. In arithmetic, John of Sacrobosco's (d. c. 1244–56) *Algorismus vulgaris* was a widely used text that introduced students to fractions, Hindu-Arabic numbers and consequent calculations involving them.[44] To this, one may add Jordanus de Nemore's (fl. 1230–60) *Arithmetica* and *De numeris datis* (dealing with problematic analysis in the Greek tradition)[45] and the work of perhaps the most talented medieval mathematician, Leonardo of Pisa's (c. 1179–p. 1240) *Liber quadratorum* and *Liber abaci*, which deals with number theory, roots and first-degree equations.[46]

In the geometrical tradition, a principal text was Euclid's *Elements*, whose various translations we have already surveyed. Beyond these, there were derivative texts like Bradwardine's *Geometria speculativa* and Jordanus de Nemore's *Liber phylotegni de triangulis*. Medieval authors also produced texts on the practical applications of geometry, in disciplines midway between natural philosophy and mathematics known as the *scientiae mediae*. In the field of statics, Jordanus' *De ponderibus* combined the Archimedean geometrical tradition with a dynamic tradition derived from the pseudo-Aristotelian *Mechanical Problems*. His text spawned a number of fourteenth-century treatises that developed this hybrid tradition still further. In the field of optics, two authors stand out as significant viaducts of high medieval visual theory. John Pecham's (c. 1230–92) *Perspectiva communis* surveyed the geometrical as well as the anatomical, physical, and psychological aspects of vision, as does Witelo's (d. 1275/80) *Perspectiva*. Both texts survive in numerous manuscripts from the fourteenth and fifteenth centuries; Pecham's achieved ten printed editions before 1600, Witelo's three. The surviving manuscripts and witness of institutional statutes suggest that both works served as the standard texts in perspective at universities across Europe in the late Middle Ages.[47]

Although Ptolemy's *Almagest*, available in Latin translation since the twelfth century, was the foundation of Western astronomical theory, it was rarely used. Instead, medieval university astronomy was based largely on two derivative texts. Sacrobosco's *De sphera* was prescribed in virtually every university curriculum and survives in several hundred manuscript copies in libraries across Europe. With the advent of printing, this popularity was transferred to the new medium: 35 editions were printed in Venice alone and more than 100 elsewhere in Europe. The irony of this is that it achieved such success despite (or perhaps because of) its rather modest astronomical content, since it provided little discussion of planetary models. To supplement this deficiency, medieval scholars used an anonymous text known as the *Theorica planetarum*, the most famous of which bears the incipit 'Circulus eccentricus vel egresse cuspidis ... .' Although it also possessed notable flaws of detail, which Renaissance astronomers criticized, it provided both a coherent theory of planetary motion and a stable astronomical vocabulary. So great was its reputation in the university that it continued to function as a basic text well after the initial publication of Copernicus' *De revolutionibus*.[48]

While astronomers used the *Sphere* and *Theorica* for a general plan of the cosmos, they drew upon the Toledan and Alfonsine Tables for specific data with

which to calculate planetary positions. The former was assembled in the late eleventh century and supplanted in Spain only after about 1272, when a panel of translators and astronomers under Alfonso the Wise improved upon them. Outside Spain, however, the Alfonsine Tables failed to achieve wide circulation until about 1320, but when it did so, it became the standard compendium until the sixteenth century.[49]

Of course, any discussion of the literature of science in the Middle Ages must include those texts that go beyond narrowly scientific genres. Alexander Murray has observed recently that something like a third of the continuous cosmological speculation in the Middle Ages is contained in commentaries on the book of Genesis, the so-called hexameral tradition.[50] The 850 medieval commentators on Aristotle referred to above produced a total of some 11,000 works, indicating that the place of Aristotle within their general interests was somewhat smaller than one might otherwise think. Among those other interests, it is not surprising to find that theology ranked high: nearly 900 works can be classified as generally theological in orientation, with a further 800 commentaries on Scripture.[51] As a group, the commentators on Aristotle also produced some 330 commentaries on the *Sentences*, works which historians of science beginning with Anneliese Maier have shown to be especially rich in material of scientific interest.[52] Finally, this cohort produced nearly 900 quaestiones disputatae of various types,[53] a further 135 logical texts comprising sophismata, obligationes, insolubilia, consequentiae and suppositiones,[54] and another 130 natural philosophical texts including latitudines formarum, calculationes and proportiones motuum. Historians of science surveying the scientific *Nachlass* of medieval scholastics will find a rich, if frustratingly diverse store of materials.

Still another rich storehouse of material for medieval science can be found in the medieval literary tradition. The medieval literary traditions of Natura, themselves dependent on the transmitted classical philosophical and literary heritage, produced astonishingly varied perspectives: Hildegard of Bingen (1098–1179), whose dynamic cosmological speculations are revealed through the fabula tradition, Bernard Silvestris, whose *Cosmographia* (a. 1147) also presents Nature's creative powers under the fabulous mode of expression, or Alain de Lille (d. 1203), whose *De planctu naturae* and *Anticlaudianus* drew heavily on the neo-Platonism of the school of Chartres and influenced in turn the work of Jean de Meun (c. 1275), Chaucer (d. 1400) and Dante (d. 1321), whose works conveyed their own scientific and especially cosmological conceptions. Beyond their intrinsic literary significance, these texts provide an understanding of the technical and non-technical transmission of science in a more popular mode, and permit a more extensive historical investigation of controversial issues, like astrological determinism and alchemy, within the general population.[55]

Before concluding this chapter, it may be useful to discuss briefly the vehicle for the transmission of the texts discussed above, the manuscripts themselves. The production of manuscript copies during the Middle Ages occurred in a variety of ways, in monastic and other ecclesiastical scriptoria, by professional scribes em-

ployed by university stationers or others, or by the users themselves, often the masters and students in the university. As one might expect, in both the media on which the text was written and the reliability of the text transmitted, there is considerable variation in quality. Many of the manuscripts that contain materials of historical interest were produced by scholars for their own use and, for reasons of economy and expediency, the scholar-scribe expended careful labour only to the extent that he could read his copy. Frequently, these copies contain the personal transcriptions or reportationes of university lectures, valuable for their content, but difficult to assess and compare when one has multiple versions of classroom transactions. Furthermore, since 1935 textual critics have recognized that copies derived from university stationers were often reproduced under the pecia system, a practice that produced contamination of pure textual traditions and makes establishment of the text difficult. Finally, as E. P. Bos has observed recently, in many philosophical texts, scholars transcribed not *de verbo ad verbum*, but *ad sensum*, so that while the manuscript text preserves the meaning (at least as the copyist understood it), finer details may be more elusive.[56]

The problem of locating scientific texts within manuscripts, although still a difficult problem, has been facilitated in recent years by several important bibliographical tools. Even with its several addenda, Thorndike and Kibre's *Incipits of Medieval Scientific Writings in Latin* is now somewhat dated, and does not contain complete and exhaustive references to the manuscript sources.[57] Many of the individual repertoria or bibliographies mentioned previously in notes to this chapter will provide additional information, but in addition, Paul Kristeller's *Iter Italicum*, though focused on the Renaissance, is an essential finding list for manuscripts of medieval authors as well.[58] Two serial bibliographies deserve special attention. Since 1978, *Medioevo latino* has published an annual listing of work pertaining to authors from the sixth century to the thirteenth century, and many entries pertain to scientific material construed broadly. Since 1991, the *Bibliographie annuelle du moyen âge tardif* provides much the same material for authors between 1250 and 1500.[59] Finally, Sigrid Krämer's revised and enlarged edition of Kristeller's *Latin Manuscript Books before 1600* is an incomparable source for locating manuscript catalogues worldwide.[60]

Notes

1. The first but partial edition of Boethius' works was printed in Venice by Johannes and Gregorius de Gregoriis, 1491–92 (reprinted 1498–99); a complete edition appeared in Basel (1546). The individual works are too numerous to survey here, but the enormously popular *Consolatio* was edited first c. 1471, with over 60 Latin editions printed before 1501; most recently it has been edited by L. Bieler (1957). Critical editions of Boethius' translations of Aristotle may be found in the *Aristoteles latinus* (1961–) series. The treatises on arithmetic and music may be found in Friedlein (1867). The Boethian *Elements* survives in fragments, as the so-called third recension of Cassiodorus' *Institutiones*, in the *Corpus agrimensores*,

and in the pseudo-Boethian *Geometry* I and II; see Folkerts (1989). Among the vast secondary literature, see M. Gibson (1981) for an assessment of both Boethius and his subsequent impact on Western European culture; the particular influence of Boethius' theological writings, especially in the twelfth century, was undertaken by N. Häring (1971).

2. For the most recent edition of *De nuptiis*, see Willis (1983); for a list of manuscripts, printed editions, and commentaries on the text, see Lutz (1971) and Lutz and Contreni (1976). Stahl and Johnson (1971–77) provide an English translation and analysis of the text.
3. Concerning the *Institutiones* and its textual tradition, see the excellent edition of Mynors (1937). L.W. Jones (1946) provides a survey of Cassiodorus' work in addition to a translation of the text.
4. Díaz y Díaz (1959) provides a list of Isidore's works. The *Etymologies*, which survives in more than 1000 manuscript copies, is being edited under the direction of Jacques Fontaine (1981–); when complete, it will replace the old edition of Lindsay (1911). Fontaine (1960) has also edited *De natura rerum*. As an example of the inconsistencies presented in these encyclopaedic accounts, note that in XIII.2–3 of the *Etymologies*, Isidore presents in sequence both the Atomist and Aristotelian accounts of matter and the elements without commenting on their opposing ontologies, and often misunderstanding the intentions of the original arguments.
5. For editions of Bede's works, see Migne, PL xc-xcv (1861–62) and the new editions in *Corpus Christianorum, series latina* (CCSL) (1960–). In particular CCSL vol. 123 (1980) contains editions of successive versions of *De temporibus*. For a list of manuscripts containing Bede's works, see Laistner and King (1943), and for recent assessments of Bede's life and work, Brown (1987) and Ward (1990).
6. For editions of his works, see Gerbert d'Aurillac (1867), and for an assessment of them, Lindgren (1976) and Struik (1972).
7. There is by this time a rather extensive literature on the translation movement of the twelfth century, beginning with Steinschneider (1893) and (1904–5) and Wüstenfeld (1877). A pioneering study was Haskins' 'The Translations from Greek and Arabic', chapter nine of his famous *Renaissance of the Twelfth Century* (1927). For additional and more recent evaluations, see Muckle (1942–43), Kristeller et al. (1960–), Lindberg (1978) pp. 52–90, d'Alverny (1982) and her collected articles on transmission (1994b), and Ragep and Ragep (1996), as well as many of the more specific studies in the notes which follow.
8. Concerning James, see Minio-Paluello (1952), (1972) and (1973); Vuillemin-Diem (1974) and Franceschini (1976). See also the introductions to several of the *Aristoteles latinus* volumes, esp. IV.1–4 and XXV.1.
9. Concerning Moerbeke, see Grabmann (1946), Minio-Paluello (1974) who includes a list of works translated by Moerbeke, and Clagett (1964–84) vol. 2, pp. 3–13, 28–53 and vol. 3, pt. 3, ch. 4.
10. For a revision of Sarton's list of Gerard's translations, see Lemay (1978). Gerard's translation of the *Elements* survives in some 16 manuscripts, and has been edited by Busard (1984).
11. Thorndike (1959).
12. The two Roberts have often been confused. Robert of Ketton was an associate of Hermann of Carinthia, and Peter of Poitiers indicates that this Robert had become archdeacon of Pamplona when Robert of Chester was in London. Together with the distinction in the names preserved in twelfth-century manuscripts, this serves to distinguish the two translators. I am grateful to Richard Sharpe for calling my attention to this detail. Concerning both Roberts, see Steinschneider (1904–5), Martín Duque (1962); d'Alverny (1982) p. 449 and n. 119; and Karpinski (1930).
13. Concerning Hermann (also known as Hermann von Carinthia, or 'Sclavus'), see

Burnett (1978), Silverstein (1955) and Lemay (1962). Hermann's translation of the *Elements* may be found in Busard (1967/1972).

14. See Clagett (1970) for a list of works and translations; d'Alverny (1982) esp. pp. 440–43; and Murdoch (1968). The standard initial treatment of Adelard's translations of Euclid was Clagett (1953), who distinguished three versions of the *Elements* attributed to Adelard, and designated Adelard I, II and III. Since that time, Folkerts (1989) has argued that Adelard II, the most popular of the versions with more than 50 manuscripts, was the work of Robert of Ketton, and Adelard III, already recognized by Clagett as a commentary rather than a translation, derives from the end of the twelfth century. Adelard I, which survives in some seven manuscripts, was edited by Busard (1983); Adelard II by Busard and Folkerts (1992); and the introduction to Adelard III by Clagett (1954).
15. D'Alverny (1982) pp. 457–59; and see also the general histories of the translation movement listed in n. 7 above.
16. I do not wish to imply by this that the process was either linear or passive. There are several instances in the translation movement, particularly in the thirteenth century, that were occasioned by the assimilation process. The model Sabra (1987) has proposed for Islamic appropriation of ancient science can often be seen at work *mutatis mutandis* in the Latin European scene.
17. See the example of Isidore of Seville discussed above, n. 4.
18. *Aristoteles latinus, Codices*, two volumes and supplement (1939–61).
19. Concerning Albert's role in the assimilation of the new science, see several of the essays in Weisheipl (1980). New editions of Albert's works were undertaken beginning in 1951, under the guidance of Bernhard Geyer; for a list of Albert's works, together with the manuscripts and editions in which they are contained, see Fauser (1982).
20. For this material, I have drawn upon the insightful analysis of Parkes (1976).
21. For a recent bibliography of work on Vincent and the *Speculum*, see Kaeppeli and Panella (1993) pp. 435–36, who have also compiled a list of manuscripts and editions containing the *Speculum* (pp. 437–47). The work was also translated in the middle ages into Catalan, French, German, Italian and Dutch (pp. 447–49).
22. Partial edition (1979) ed. Lond, R. James. Bartholomew's work was translated into six languages and printed several times before 1601. One of its primary functions was the provision of material about natural effects for preachers.
23. Ed. Carmody (1948).
24. Leff (1992) p. 318 and van Steenberghen (1955).
25. An interesting and important example of this has been analysed by Weisheipl (1982): the idiosyncratic understanding of form and nature in Avicenna, which was criticized in the thirteenth century by Aquinas.
26. D'Alverny (1961–72), now collected and augmented in one volume (1994a) by Simone Van Riet and Pierre Jodogne. For additional studies on the Latin Avicenna, see d'Alverny (1993).
27. *Avicenna latinus* (1968–); thus far, the *Metaphysics* (3 vols, 1977–83), *De anima* (2 vols, 1968–72), *De generatione et corruptione* (1987), and *De actionibus et passionibus qualitatum primarum* (1989) have been edited by the late Simone Van Riet.
28. Under the sponsorship of the Mediaeval Academy of America, Averroes' commentaries are being edited in the surviving Arabic, Hebrew and Latin forms and also translated into English. Wolfson (1963) provided a revised prospectus for the project, and a few volumes, notably the Epitome of the *Parva Naturalia*, the Great Commentary on *De anima*, and the Middle Commentary on *De generatione et corruptione*, have been published. A list of Latin translations of Averroes' commentaries, together with a count of surviving manuscripts, is furnished by Dod (1982) pp. 74–78. The texts themselves were published in the Junta edition (1575), supplemented on some

occasions by the previous editions of Cominus de Tridino (1560), Andreas Torresanus de Asula and Bartholomaeus de Blavis (1483), and Philipus Venetus (1481).

29. As an example, see Maloney's edition of Bacon's *Compendium studii theologiae* (1988), esp. sections 69–82.
30. Particularly on the unity of the agent intellect and the place of theology in the hierarchy of the sciences. See the text of the condemnations in *Chartularium Universitatis Parisiensis*, ed. Denifle and Chatelain vol. 1 (1889) no. 473, esp. props. 116–22, 125–27, 145, 150 and 154.
31. Concerning Siger, see Bazan (1974). The works of Boethius of Dacia have been edited in the series *Corpus philosophorum Danicorum medii aevi* (1974–). Concerning the controversy surrounding John of Jandun, see MacClintock (1956) and Ermatinger (1969). For an introduction to the works of Paul of Venice, including manuscripts and early printed editions, see Perreiah (1986). For a recent evaluation of Latin Averroism, see Kuksewicz (1995).
32. For a catalogue of Lull's work, see the recent work of Bonner (1989) and Bonner and Badia (1988). The Latin works are being edited in *Corpus Christianorum*, Cont. Med. (1975–).
33. The fundamental treatment of the reception of Aristotle into the schools is Grabmann (1939), supplemented for the English schools by Callus (1943). The reception of Aristotle in Europe was given an enormous assistance by the catalogue of commentaries made by Charles Lohr (1967–74). Subsequently, this list was augmented and corrected by a number of more specialized studies, including inventories of Aristotle commentaries in particular libraries; see Korolec (1977) for Prague, Lohr (1994) for Switzerland, Lohr (1982, 1988) for France, Markowski (1987) for Erfurt, Markowski and Wlodek (1974) for Cracow, Markowski and Wlodek (1985) for Vienna, Pattin (1978) for Belgium, de Rijk and Weijers (1981) for the Netherlands and Senko (1982) for Paris. Beyond this, other scholars have focused on particular Aristotelian works to produce repertoria of commentators that occasionally supplement or correct these geographical studies; see for example Slomczynska (1986) for the *Economics*, Flüeler (1987) and (1992) for the *Politics*, Marenbon (1993) and Ebbesen (1993) for the logical works, or Green-Pedersen (1984) for the *Topics*. For a recent assessment of the state of medieval Aristotle studies, see Brams (1997). The following numerical analysis is based on my own electronic database of commentators that incorporates these and other sources (including catalogued and uncatalogued manuscript texts), and reflects the data current at the time of writing.
34. Recent biographical accounts of Grosseteste, together with lists of his works, suggestions about dates of composition, and editions can be found in McEvoy (1982) and Southern (1992).
35. Concerning Buridan's work, especially on impetus, see Maier, *Zwei Grundprobleme* (1968) pp. 201–28 and Clagett (1959) pp. 522–37, who provided editions of the relevant sections of Buridan's *Quaestiones in VIII libros Physicorum* (Paris: Petrus Ledru 1509). For a list of Buridan's commentaries on Aristotle and manuscripts in which they are found, see Lohr (1970) pp. 161–83. Buridan's work in general was surveyed first by Faral (1946), whose positions have often required revision over the past fifty years; for a recent reevaluation of Buridan's opera, see Michael (1985).
36. Concerning Albert of Saxony, see the recent work of Sarnowsky (1989). The extensive range of Albert's works can be seen in Muñoz García's bibliography (1990); more recent secondary literature is collected in Berger (1994).
37. The role of Marsilius in fourteenth-century philosophy, science, and theology (and their interrelationships) was investigated first by Ritter (1921). In the past decade, his work has received renewed attention by several scholars, but especially M. J. F. M. Hoenen (1993), Braakuis and Hoenen (1992), and Wielgus (1993). For a complete bibliography of Marsilius' work, see Hoenen (1989/1990).

38. Buridan's arguments were developed in his *Quaestiones super libris IV De caelo et mundo*, ed. E. Moody (1942), vol. II, q. 22; Oresme's reply can be found in *Le Livre du ciel et du monde*, ed. Menut and Denomy (1968), vol. II, ch. 25. For a list of Oresme's works, see Menut (1966, 1969) and Clagett (1968) pp. 645–48. Some of Oresme's potentially interesting works have been difficult to trace. Markowski (1982) postulated the rediscovery of Oresme's *Quaestiones super VIII libros Physicorum* in several manuscripts, including Erfurt, B. Ampl. F.298, f. 1v–45; still earlier, Boehner (1947) discovered a single question from Oresme's commentary on the *Sentences* in Paris, B. Maz. 893, ff. 161–64. For a recent perspective on Oresme and his writings, see the introductory material in Hansen (1985).
39. In addition to his theological works, de Marchia also composed commentaries on Aristotle; see Lohr (1967) pp. 411–12. De Marchia's cosmological speculations have been analysed recently by Schneider (1991).
40. Contained in *In Physicam Aristotelis*, VIII; Erfurt, Amplon. Q.312 (at fol. 13va–vb). See Wood (1992). For a list of Rufus' writings, see Raedts (1987), although Wood and others have challenged his classification of some works as spurious.
41. See Crosby (1955) for an edition and translation of *De proportionibus* and a list of manuscripts and early editions of the work. *Geometria speculativa* has been edited by Molland (1989); for the mathematical foundations of Oxford physics and Bradwardine's role, see Molland (1968). His *De continuo* has been analysed by Murdoch (1957) and Zubov (1960) for fourteenth-century views on space. Bradwardine was also the author of a widely read theological text, *De causa Dei*, written to combat what Bradwardine saw as the rise of modern Pelagianism. The text was edited in the early seventeenth century by Merton College fellow and underwriter of the sciences at Oxford, Henry Savile. Recently, fragments of Bradwardine's commentary on the *Sentences* have been found in Paris, BN lat. 15805 by Genest and Tachau (1990).
42. For an excellent introduction to these topics, see Murdoch and Sylla (1978). The transmission of the Calculators' and Oresme's texts was surveyed by Clagett (1959), ch. 11. See in addition Sylla's analysis (1987) of the place of these texts in the late-medieval scholastic curriculum and its relationship to the transmission of the texts. For a survey of the works of Heytesbury, Dumbleton, Swineshead and others at Merton College in the early fourteenth century, see Weisheipl (1969). Heytesbury's *Regule* was analysed by Wilson (1956), who also provided a list of manuscripts and early editions of the text.
43. For a list of the 31 extant and references to five lost manuscripts of the *Letter*, see Schlund (1912); for a list of the 11 printed editions, beginning with the Augsburg 1558 edition, see Thompson (1905–6). A comprehensive biography and bibliography can be found in Grant (1974).
44. Little is known of Sacrobosco's origins; Holywood or Halifax in England is often taken as his place of birth. His academic career seems to have been spent largely at the University of Paris. Concerning his life and the circulation of his work, see Thorndike (1949).
45. Information about Jordanus is very scarce indeed. A reference to him in Richard de Fournival's *Biblionomia* places him before 1260, and his acquaintance with al-Khwārizmī's algebra requires that his work be after 1145; nineteenth-century identifications with the artist and theologian Jordanus de Saxonia have been shown to be false. Concerning his mathematical work and its circulation, particularly in the case of *De datis*, see Hughes (1981).
46. The son of a Pisan mercantile dignitary, Leonardo spent his youth in Bugia, Algeria, where he learned the elements of Hindu-Arabic numerical methods, which served as the basis for his mathematical writings. His reputation was sufficiently great to warrant an audience with Frederick II in 1225, and in 1240 he was on retainer to the

Republic of Pisa in matters of accounting. For a discussion of his life and work, see Vogel (1971); editions of his works may be found in Boncompagni (1857–62).

47. For a discussion of Pecham's life and work, as well as an edition and translation of the *Perspectiva*, see Lindberg (1971). Witelo's *Perspectiva* is being edited and translated by Unguru, Smith and Bieganowski; to date, books 1–5 have appeared (1977, 1983, 1991, 1994), together with significant discussions of Witelo's theoretical achievements, the manuscript tradition of his text, and the place of his *Perspectiva* in the general European optical tradition.
48. Concerning Sacrobosco and the *Sphere*, see Thorndike (1949) and Pedersen (1985). For a discussion of the origins and the content of the *Theorica*, see Pedersen (1981).
49. Concerning the Toledan Tables, see Toomer (1968); for the Alfonsine Tables, North (1988) pp. 147–49.
50. Murray (1992) p. 41.
51. The standard repertorium for medieval biblical commentaries is Stegmüller (1951–61; 1976–80).
52. Although incomplete and frequently in error, the fundamental repertorium of commentaries on the *Sentences* is Stegmüller (1947), supplemented by Doucet (1954). Van Dyk (1979) provided a retrospective analysis of related work on the topic, and a new comprehensive edition of the repertorium has been announced by Charles Lohr (1990), in *Bulletin de philosophie médiévale*, 32, 57. The use of commentaries on the *Sentences* as sources for the history of science is far too extensive to survey, but one of the pioneering studies is Miss Maier's five-volume series of studies (1952–68).
53. Concerning the use of quaestiones disputatae, see in particular Bazan (1982) and Lawn (1993). A somewhat dated repertorium of quodlibetal literature is Glorieux (1925, 1935).
54. For a discussion of each of these forms and their significance for late-medieval philosophy and science, see Kretzmann et al. (1982) ch. 11, 12, 15, 16. For a repertorium of insolubilia literature, see Spade (1975); for obligationes, Ashworth (1994).
55. For a survey of the figure of Nature in medieval literature, see Economou (1972), who provides additional bibliography for most of the authors mentioned here. Additionally, see Dronke (1974) for Hildegard's cosmological speculations, and Stock (1972). For Chaucer's understanding of science, see North (1988), who argues that Chaucer achieved an astronomical accuracy in contrast to Dante's 'grandiose cosmological scheme' (p. 2). For an overview of the alchemical tradition, see Robert Multhauf's chapter in Lindberg (1978), as well as the excellent introduction, edition and translation of pseudo-Geber by Newman (1991).
56. The fields of paleography, codicology, diplomatics and transmission of texts are much too extensive to survey here, but the reader may be referred to Boyle (1984) for a bibliographical treatment of many of these areas. For the university book trade and pecia techniques in particular, see Destrez (1935), Pollard (1963) and Rouse and Rouse (1988). See also Bos (1983) pp. 33–34.
57. Thorndike and Kibre (1963). Linda Ehrsam Voigts has suggested recently that an updated version of this work will be prepared for electronic publication by the Medieval Academy of America.
58. Kristeller (1963–); an electronic edition of the work has been prepared by Luciano Floridi, in Kristeller (1995), making searches of this vast resource considerably easier. It is frequently necessary to consider the complete intellectual output of a historical figure, including works that have not survived. For such cases, medieval library catalogues are often very helpful. For the German-speaking world, two series are especially useful: *Mittelalterliche Bibliothekskataloge Deutschlands under der Schweiz*, 4 vols in 8 parts, Munich: C.H. Beck'sche Verlagsbuchhandlung,

1918–79; and *Mittelalterliche Bibliothekskatalogue Österreichs*, 5 vols in 6 parts, Vienna: Holzhausen, 1915–71. A notable recent addition to this literature is the *Corpus of British Medieval Library Catalogues* (1990–), now under the general editorship of Richard Sharpe. When complete, these will vastly improve our understanding of the range of medieval scholarship. For private collectors (again in England), see Cavanaugh (1980).

59. *Medioevo latino* (1978–); *Bibliographie annuelle du moyen âge tardif* (1991–). In addition, annual volumes of the *Bulletin de philosophie médiévale* (BPM) (1959–) may be consulted for current work in the field; several foundational repertoria of medieval authors published originally in the BPM have been referred to previously in this chapter.
60. Kristeller (1993), ed. Krämer.

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Chapter Three

Transitions 2: Islamic Science

Jacques Sesiano

Introduction

The Islamic science forming the subject of this essay encompassed studies of natural and exact sciences in the Islamic world roughly during the time of the European Middle Ages. The main centre was at first Baghdad, founded in 762, where the encounter with foreign science and the birth of Islamic science took place. In the tenth century, the western Islamic world (principally Spain) became separated from the eastern part, and there was afterwards little contact between the two. From the eleventh century on, scientific centres shifted from Baghdad westwards to Egypt and eastwards to Persia and later on farther to central Asia; observatories, which had in some way a role comparable to that of the universities in Mediaeval Europe, are landmarks of this displacement. Studies in the Islamic countries were in Arabic, although Persian was also used. Persian gained a growing influence from the fourteenth century on; from that time Turkish is also found. The situation is analogous to the European one, since towards the end of the Middle Ages more accessible scientific treatises were often written in vernacular languages instead of Latin.

But if the developments in the Islamic world and in Christian Europe show some similarity in the late Middle Ages, it was not, indeed could not be, the case at the beginning of Islamic science, when Europe knew its first (Carolingian) renaissance. Whereas hardly anything from ancient science was available in the Latin world, Islamic scholars were the beneficiaries of three heritages. The first was local, scattered in former Hellenistic cultural centres which maintained remnants of knowledge of Greek, Persian or Mesopotamian origin. The second and more important heritage, but the one received last, was the legacy of

classical Greek science, obtained by means of translations made directly from the Greek and mostly in the ninth century, although translation activity is already witnessed in the eighth century and in some cases Syriac and Persian may have served as intermediaries. Finally there is the Indian contribution, which differed from the other two in that Indian science was living and expanding and therefore direct contacts and transmission were possible, and indeed took place at the beginning of Islamic science, before the influence of the Greek heritage became predominant.

Many Arabic texts were translated into Latin in the twelfth and thirteenth centuries, thus providing Europe with Greek science via Arabic translation as well as with original Arabic scientific writing: as a result many Islamic scientists and philosophers are still known under the latinized names given to them by mediaeval translators. Europe, however, did not get to know most of the major achievements of Islamic science until modern times, for the peak of Islamic science occurred *between the late tenth and the thirteenth centuries* and *in the eastern part*. The texts of Arabic origin available in Spain, the foremost translation centre in the twelfth and thirteenth centuries, were either from Spain itself, or, if they originated from the eastern Islamic world, they were, with few exceptions, anterior to the first part of the tenth century.

Mathematics

Although arithmetic (*hisab*) was used in Greece, the legacy of India was essential, since the Indian system of numeration, which is our present system, was adopted by the Arabs. From the earliest extant treatise on arithmetic, that by Muhammad ibn Musa al-Khwarizmi (fl. 820), the teaching of reckoning with the Indian numerals remained almost unchanged. After explaining the characteristics of the positional system with ten digits inherited from India, in which the value of the digit within the number (that is, the power of ten it multiplies) is determined by its place, the reader is taught how to add, subtract, multiply, divide, and how to extract square (sometimes also cubic) roots. This is explained for integers and common fractions, often for sexagesimal fractions as well, for they had been employed in astronomy since Mesopotamian times. Some adaptations of the arithmetical operations took place in the Islamic countries, when ink and paper replaced the dust-board on which the common operations were performed in India.

Among later innovations, one may distinguish the use of decimal fractions by the time of al-Uqlidisi (fl. 950), the separation between the integral and the decimal part being indicated by a small vertical stroke over the last integral number; several ways of approximating square and cubic roots; the algorithm of extracting roots higher than the cubic one, such as the fifth and sixth root (e.g. al-Kashi, fl. 1410); the use of the Pascal triangle for the determination of the coefficients of the integral power of a binomial expression (al-Karaji, fl. 1000).

The Arithmetic of al-Khwarizmi was translated into Latin in the twelfth century, and the name of the author was latinized as *Algorizmus* (*kh* and *g* differ in Arabic writing merely by a dot, written above or below a same sign); this name was later misread as *Algoritmus* (*z* and *t* may look much alike in mediaeval writing) and it became, through a mistakenly assumed Greek origin, our *algorithm*. Similarly, the sanskrit word *shunya* ('void') used for designating zero was appropriately translated by *sifr* in Arabic, but this latter word was then simply transliterated in Latin as *cifra* and *zefirum*, the former producing *chiffre* and *cipher* and the latter, in an abbreviated Italian form, *zero*.

As in arithmetic, al-Khwarizmi was important in algebra. His treatise on this subject is not original; but it was elementary and well written, and thus was widely read and influential on later algebraic treatises. Hence, the most important one of the early period, that by Abu Kamil (fl. 890), refers explicitly to the pioneering work of al-Khwarizmi. But, unlike its predecessor's, it is written for mathematicians and so does not hesitate to present geometrical demonstrations of algebraic relations in a true Euclidean manner, and to use (quadratic) irrationalities, both as coefficients and as solutions. Although its level was relatively high, the basic knowledge remained the same as in remote antiquity: only the six forms of linear and quadratic equations with positive coefficients ($ax^2=bx$, $ax^2=c$, $bx=c$, $ax^2+bx=c$, $ax^2=bx+c$, $ax^2+c=bx$) were solved and only a positive solution was acceptable. Abu Kamil's book already possessed the form algebraic treatises were to keep until the end of the Middle Ages: the explanation of basic algebraical reckoning and of the resolution of the six equations is followed by a large number of applications of a commercial, geometrical and recreational nature (this last way of training mathematical thinking remained part of school teaching until today; best known are the problems of pursuit or of filling a cistern with different pipes). Still another feature of Abu Kamil's Algebra was the removal from his textbook of problems of inheritance, which occupied a considerable part in al-Khwarizmi's book (however, Abu Kamil wrote a separate treatise on the subject).

In the tenth century, the Greek method (applied in a very small number of cases) of solving third-degree equations geometrically, using intersections of second-degree curves (at least one of them a conic section) was extended to various forms of the cubic equations with positive terms and an (obligatorily) positive solution. All possible cases were examined around 1070 in the Algebra of 'Umar al-Khayyami (or Omar Khayyam, to use the transliteration under which he is known in Europe for his quatrains, *ruba'yyat*). For the reason already mentioned, these last important results remained completely unknown both in Islamic Spain and Christian Europe. Perhaps it was not altogether a loss: in Italy, research took a purely algebraic course from the fourteenth century, which progressively led to the algebraic resolution of the equations of the third and fourth degrees (c. 1500–45). We may finally observe that, unlike in antiquity with Diophantus, mediaeval algebra, either Arabic or Latin, did not use any symbolism until the fifteenth century.

These Arabic treatises on algebra were entitled books on *al-jabr* and on *al-muqabala*, which designate the two basic operations used to reduce the resolving equation to one of the six standard forms (*al-jabr*, 'the restoration', transforms an equation containing negative terms to one having only positive terms, and *al-muqabala*, 'the opposition', removes the common positive quantities from both sides). The first operation, both in Arabic as in its Latin transcription *algebra*, gave its name to the science of dealing with unknowns, from c. 1000 in Islamic countries and 1150 in Christian Spain. The Algebra of al-Khwarizmi was translated into Latin at that time (but the problems on the division of estates were left out: they make sense only in the light of Islamic law). His successor's work was translated in the fourteenth century, too late indeed to have any influence: the fundamental textbook on algebra in the West had become in the meantime the *Liber abaci* by Leonardo Fibonacci of Pisa (fl. 1220), who had travelled extensively both in the Arabic world and in Byzantium, and thus acquired more mathematical knowledge than had been available in Spain.

Practical geometry (*handasa*) has its roots in the Alexandrian tradition and in more local practices (some of which are strongly criticized in Abu Kamil's treatise on the subject). It consists of formulas, or approximation formulas, for determining areas and volumes of bodies. It deals also with the measurement of heights and distances of remote objects, for which trigonometry is often required.

For theoretical geometry, the sources are exclusively Greek: Euclid, Apollonius and, for some specific problems, Archimedes. Most noticeable are first discussions about Euclid's fifth postulate (the so-called 'parallel postulate'), the acceptance of which as a postulate was already being questioned in antiquity; by continuing this, Islamic geometers such as Thabit ibn Qurra (836–901), Ibn al-Haytham (c. 965–1040), 'Umar al-Khayyami, and Nasir al-Din al-Tusi (1201–74), made beginnings in non-Euclidean geometry. The study of 'impossible problems' (that is, not solvable using only ruler and compass) was carried on, notably in the second half of the tenth century by Abu'l-Jud and al-Sijzi: trisection of the angle, construction of the side of the regular heptagon and enneagon, all of which lead to cubic equations, whereas ruler and compass allow only the construction of problems of the first two degrees; another major contribution by al-Khayyami has already been mentioned above. The intensive use of conics led to the invention of a compass with one leg of variable length for drawing them (al-Quhi, second half of the tenth century). The influence of Archimedes is seen in the determination of the area limited by a segment of a parabola, the calculation of the volumes and of the centres of gravity of given bodies of revolution (Thabit ibn Qurra, al-Quhi, Ibn al-Haytham); it required, as had been the case for Archimedes, the consideration of infinitesimal quantities, hence all these scholars have been considered in one way or another as forerunners of calculus.

Plane trigonometry was based in Greece on the consideration of chords and in India of half-chords. This latter form, adopted and extended to the six basic

trigonometric magnitudes by Islamic mathematicians (completed by Abu'l-Wafa' al-Buzjani, 940–997/8), is the one in use today. Spherical trigonometry depended mainly upon Greek treatises on spherics, even if it took its modern form in Islamic countries. In the Islamic world trigonometry had long been expounded among instructions for the use of astronomical tables until it became, at its peak, an independent branch of mathematics with al-Tusi.

Number theory is characterized by two main topics, both of which stemmed from Greek knowledge. One of them is the relation between a natural number n and $s(n)$, the sum of its integral divisors excluding itself; the number n was then either 'abundant' if $s(n)$ is larger than n (like 12, for $s(12) = 1 + 2 + 3 + 4 + 6 = 16$), 'perfect' if $s(n) = n$ (like $6 = 1 + 2 + 3$), 'deficient' if $s(n)$ is smaller than n. All this is Greek, but apparently novel is the search for a number n such that $s(n)=k$, with k given, about which al-Baghdadi (d. 1037) incidentally asserts that there is no such n if k equals 2 or 5 (according to what we know today 5 is the only odd number for which this is not true whereas exceptions are relatively common for k even). Like the Greeks, Islamic mathematicians considered pairs of 'amicable' numbers, that is to say numbers n_1, n_2 such that $s(n_1) = n_2$ and $s(n_2)= n_1$, of which the Greeks knew only one pair (220, 284). Now, Thabit ibn Qurra found and proved in true Euclidean manner a way of finding other pairs. Although of very restricted application, it was nevertheless the first successful attempt to compute pairs.

Two Greek sources inspired Islamic mathematicians in their study of quadratic indeterminate equations with positive rational solutions. The principal one is Diophantus' *Arithmetica*, of which seven of the original thirteen 'books' (that is, large chapters) were translated into Arabic. The other one is unknown to us today but was the origin of a set of indeterminate equations solved in Abu Kamil's *Algebra*, the author telling us that such problems were the subject of discussion in his time. A good introduction to Diophantine methods occurs in al-Karaji's *Badi'*. The theoretical approach to the solution of finding a square which, increased or diminished by a given integer, produces in both cases a square was treated in the first half of the tenth century by al-Khazin; it became later the central subject of Leonardo Fibonacci's *Liber quadratorum*.

Linear indeterminate equations with positive integral solutions were the subject of a separate treatise by Abu Kamil, who searched for all such solutions for six pairs of linear equations with three to five unknowns. Attempts to prove the impossibility of solving $x^3 + y^3 = z^3$ in rational numbers are found in the tenth century.

Finally, the science of magic squares (*wafq*) (that is, how to fill a square divided into a square number of cells with a sequence of different natural numbers in such a way that the same sum appears in each row and column and in the two diagonals) is the most original mathematical contribution of Islamic science. It may have originated, like some other summation problems, with the chessboard (introduced to Persia from India sometime around the seventh century). Treatises devoted to this subject are known to have been written in the

ninth century, but the earliest extant ones are from the tenth century (one by al-Buzjani); they become common in the twelfth century. By that time, various methods have been devised for constructing squares of any given side with n cells, thus to n^2 cells, with n integral larger than 2 (n=2 leads to identical numbers) as well as squares subject to further conditions. Later, the application of these squares for various magical purposes became predominant. In the fourteenth century, mediaeval Europe learned of these squares from such magical texts and thus arose their modern name. Islamic construction methods have been studied only in recent years.

Astronomy

Astronomy in Islam had the usual purpose of establishing tables for the planetary motions and the concern inherited from Greece of representing by a combination of uniform circular motions the movement of these bodies. But a knowledge of astronomy was also required for religious purposes: praying five times a day at precise hours imposed the determination of local time for every geographical longitude and latitude; facing Mecca during the prayer necessitated the determination of its direction (*qibla*) from any place on the Earth.

Astronomical tables (*zij*) were already compiled in the eighth century; they depended upon the Indian tradition and earlier Persian tables, thus only indirectly on certain Greek sources (on which both Persian and Indian astronomy had relied). In the first important astronomical tables, those compiled by al-Khwarizmi during the caliphate of al-Ma'mun (813–33), the background, particularly for trigonometry, is mainly Indian and depends upon the *Sindhind* (a sanskrit astronomical treatise), but Greek (Ptolemaic) elements do appear. In the eighth and ninth century, several translations were made of Ptolemy's *Almagest* and of other minor astronomical Greek works (the now-standard designation *Almagest* is the Arabic transcription of an abbreviated Greek designation). The exclusive use of the Ptolemaic system occurs in the late ninth century with al-Battani's (Albategnius) astronomical tables, where he makes intensive use of spherical trigonometry, determines the increment since Ptolemy's time of the solar apogee and improves the values known for the inclination of the ecliptic (*De scientia stellarum*, without the tables, translated in the twelfth century, printed Nuremberg 1537, and Bologna 1645). But the older form of astronomy still flourished in Spain, where al-Majriti ('the Madrilenian', fl. 980) commented on and improved al-Khwarizmi's tables. The names of some astronomical tables illustrate the shift of the scientific centres from Baghdad to other towns of the Islamic world. Ibn Yunis's *Hakemite tables*, dedicated in 1007 to the Fatimide ruler al-Hakim II who built Cairo's observatory, improve most of the previous observations. Al-Zarqali (Arzachel) composed around 1075 the *Toledan tables* (*Canones in tabulas tholetanas*, printed in Nuremberg in 1534), and he shows the movement of the solar apogee relative to the stars. Instances on the other

side of the Islamic world are the *Masudic Canon*, dedicated to sultan Mas'ud by al-Biruni (973–1048), an encyclopaedia of astronomy dealing with chronology, trigonometry, mathematical geography, then astronomy itself and, at the end, a chapter on astrological operations, and the *Sanjari tables* by al-Khazini (fl. 1115, by birth a Byzantine slave-boy) in Marw. Reflecting political changes are the *Alfonsine tables*, completed in 1272 by scholars of former Islamic Spain for the Christian king Alfonso X of Castile (*Tabulae Alfontii*, printed by Ratdolt in Venice in 1483), and the *Il-Khani tables*, made contemporaneously for the Mongol king Hulagu Khan by al-Tusi, who was his vizir and the head of the observatory built in 1259 at Maragha. The last tables of fame, a revision of the previous ones, were compiled in 1414 by al-Kashi for the ruler (and astronomer) Ulugh Beg in Samarkand; they also found their way to Europe, but in modern times (*Tabulae Ulugh-Beighi*, printed in Oxford in 1665).

Either for the sake of improved accuracy, or by way of reconsidering some of the basic hypotheses, attempts were occasionally made to modify the Ptolemaic system. In the east, new models for Mercury and the Moon were invented, which, while giving essentially the same results as Ptolemy's models, kept the traditional requirement of involving only uniform circular motions (al-Tusi and Qutb al-Din al-Shirazi in the thirteenth century; later the Damascene Ibn al-Shatir, fl. 1350). On the other side of the Islamic world, in twelfth-century Spain, a revision of Ptolemy's *Almagest* was undertaken by Jabir ibn Aflah (Geber Aven Afflah) in Seville (*De astronomia*, printed in Nuremberg in 1534), while a return to the older Eudoxean-Aristotelian theory of material homocentric spheres was proposed by Abu Bakr ibn Tufayl (Abubacer) and al-Bitruji (Alpetragius; *Theorica planetarum*, translated respectively in 1217 and 1528, the latter printed in Venice in 1531). According to Alpetragius, there are nine rotating spheres, the ninth rotating uniformly about the axis of the universe in more than a sidereal day and giving the power to rotate to the interior spheres (which carry the fixed stars and the seven planets) in an increasingly attenuated form; these interior spheres revolve about two axes (fixed stars) or three (planets).

In order to improve the tables, precise instruments were required, the principal one being the astrolabe, already known in Greece, which was not only used to determine the altitude of stars, but also to determine time, measure angles and also distances, heights or depths on the Earth. The astrolabe, already described in the late eighth century by Masha'allah (*De compositione astrolabii*, printed first with the Strasbourg 1512 edition of Reisch's *Margarita philosophorum*), was later considerably improved, and some parts of the astrolabe still bear Arabic names. Al-Zarqali invented a new type of plane astrolabe presenting two stereographic projections on a single plate (called in Arabic *safiha* and in Latin *saphea Arzachelis*). This was only one among many instruments to which treatises are devoted; al-Khazini describes the construction and use of a triquetrum, a dioptra, a quadrant and other instruments. We also possess the description of the astronomical instruments at Maragha by the astronomer in charge of their construction, al-'Urdi.

Al-Sufi completed his *Illustrations of fixed stars* in 965; he relies on Ptolemy's *Almagest*, but he adds new observations and represents the constellations, a rich source of inspiration for manuscript illuminators (a beautiful example is kept in Oxford). Al-Sufi's work was widely used and is quoted several times in Hyde's edition of Ulugh Beg (Oxford, 1665, *supra*). Al-Biruni's *Tafhim*, supposedly an astrological textbook but in fact a compendium on the exact sciences, circulated both in Arabic and in Persian, thus giving a strong impulse to the scientific tradition in Persian. Finally, several new measurements of the Earth's circumference were performed. The first occurred under al-Ma'mun, for the inherited Greek value seemed grossly inaccurate; in fact, the Arabic mile was notably longer than the Roman one (the same thing happened in Europe, where the Arabic value 20,400 miles for the Earth's circumference, seen for example in Luca Pacioli's *Summa de arithmetica* of 1494, makes little sense with the miles used then in Italy). Al-Ma'mun's astronomers determined the new value by walking in the desert to the north and to the south until the height of the Pole star had respectively increased or decreased by one degree; after each group had measured the distance covered on the Earth, they took the mean value as the length of one degree on the meridian and multiplied it by 360. Al-Biruni used a much more elegant method when he saw while in India a mountain standing alone in the middle of a plain: from the knowledge of the height of the mountain and the measurement of the angle made between the horizontal at the summit of the mountain and the horizon he could infer the size of the Earth's radius (this is the method known today as the 'horizontal depression'). He could thus confirm the result found by al-Ma'mun's surveyors (owing to the imprecision of the method, there is little doubt that he had allowed himself to make small alterations in order to reach the desired value).

Physics

Greek physics was concerned with the study of movement, with optics, and with mechanical devices, both for industrial or military purposes and as automata operated by pneumatic or hydraulic pressure. In Islamic countries physics continued along the same lines.

On automata, we may note the work on ingenious devices (*hiyal*) written in the ninth century by the three sons of former robber Musa ibn Shakir; as in the Alexandrian tradition, we find in it devices of practical and industrial use, as well as toys. The best treatise on the subject, written in 1205/6 by al-Jazari, is extant in numerous beautifully illustrated manuscripts. An instrument particularly studied, to which whole treatises were devoted, notably in the eleventh and twelfth centuries by al-Biruni and al-Khazini, is the balance (*mizan*); it was used by them in particular for the determination of specific weights (see below under Mineralogy).

Of a more philosophical nature were speculations on the nature of movement. The Aristotelian view that the medium was necessary for the maintenance of the

motion of a projectile (hence no motion is possible in a vacuum) was rejected in late antiquity by Philoponos, who considered that the medium acts as a resistance and that an initial impulsion only is transmitted. These conceptions were defended by Ibn Sina (Avicenna, 980–1037) and, in the eleventh century, by the Andalusian Ibn Bajja (Avempace), the latter asserting that the velocity (not the acceleration) of a body is proportional to the difference between the initial force and the resistance of the medium and is gradually weakened during the motion. These theories were rejected in the next century by Ibn Rushd (Averroes, 1126–98) on the ground that there would be no natural movement, contrary to experience; through Averroes (and in spite of his negative opinion) these non-Aristotelian views became known and influential in mediaeval Europe.

In the ninth century, al-Kindi (Alkindus) wrote a treatise on optics (*manazir)*, both theoretical and physiological, as in the Alexandrian tradition, which was translated into Latin (*De aspectibus*). A strikingly original treatise, *Optics* by al-Hasan ibn al-Haytham (Alhazen) was translated into Latin, even though it was written in the eastern Caliphate and in the eleventh century. It was commented upon around 1300 by a student of Qutb al-Din al-Shirazi, the Persian Kamal al-Din al-Farisi, who refuted some of Alhazen's theories, such as that of the analogy between the propagation of the light and elastic collision in mechanics (an analogy on which Descartes relied also for demonstrating the law of refraction); it was also commented in the thirteenth century, but in Europe, by the Polish monk Witelo (Latin version and commentary printed together as *Opticae thesaurus* in Basle in 1572). Again, optics is treated from both the theoretical and physiological points of view. Thus, Alhazen's theory of vision deals with the transmission of the form from the seen object to the eye (this is new: antiquity considered a visual ray emitted from the eye, by means of which an illuminated object was perceived, the light from the visual ray accounting for the picture formed behind the eyes). Next, the 'problem of Alhazen', equivalent to solving a fourth-degree equation, is the geometrical determination, when the positions of two points are given and a circular, convex or concave, mirror surface is facing them, of the place at which the light emitted from one of the two points and reaching the other must be reflected. Alhazen is also known as the discoverer of the *camera obscura*, a darkened box in which the projected image of an external object, received through a small aperture, is formed; this of course correlated with his theory of visual perception. Al-Farisi discovered that rainbows were caused by the reflection and the refraction of light in drops of water. Finally, a favourite topic was burning mirrors, for which the sources were Diocles and some physicists of late antiquity.

Astrology

That the celestial bodies determine or at least influence terrestrial events is a common human belief. From it arises the hope of forecasting the future by

observing the position of these bodies relative to the Earth or to each other in the zodiac at a predetermined time, and that a calendar could be settled indicating favourable and less favourable times (*astrologia de electionibus*), and that the configuration at the birth of a human being could be determinant for his future (*astrologia de nativitatibus*). Astrology is therefore fundamentally deterministic, which may account for the opposition it met from religious authorities and some philosophers. Its assumed influence explains why it was present in other fields such as medicine and alchemy. It is also bound to the immutability of the celestial world and the geocentric system (which makes it all the more surprising to see it survive, if not rather revive, today).

Greece received astrology from Mesopotamia in Hellenistic times. Arabic astrology takes its roots mainly from Greece (Dorotheus of Sidon, Hermes Trismegistus, Ptolemy, Vettius Valens, Teukros the Babylonian), from Persia, and also from India; the intermediary role of Persian and Syriac for some Greek texts is attested. It already appeared in the eighth and ninth centuries, which was indeed the fundamental period for astrology in the Islamic world and thus also for the Christian world, since these texts were later available in Spain and thus could be translated (many of these translations were later printed). This is why most of the astrologers of this period also bear a Latin name. The following are the principal ones: Masha'allah (Messahalla), a Jew, court astrologer during the caliphate of al-Mansur (754–75), author of treatises on casting horoscopes at the time of birth (some of his works and of others were printed in Venice in 1493); his disciple Abu 'Ali al-Khayyat (Albohali), whose *De iudiciis nativitatum* is extant in two Latin versions (one printed in Nuremberg in 1546); Sahl ibn Bishr (Zahel), a Jew, first half of the ninth century (three treatises printed 1493, see above); Abu Bakr al-Hasan (Albubather), fl. 845, a Persian (*De nativitatibus*, Venice 1492 with other texts); Abu Ma'shar al-Balkhi (Albumasar), d. 885/6, also a Persian, by far the best known, whose *De revolutionibus nativitatum* (with other texts, Basle 1559) was famous not only in the Christian western world, for it had been translated from Arabic into Greek in the tenth century; finally, al-Qabisi (Alcabitius), d. 967, wrote a short introduction to astrology which was widely disseminated in mediaeval Europe (*Liber introductorius* or *libellus ysagogicus*, first printed in Bologna, 1473). These authors, although early, are the chief ones; Arabic astrology attained its peak with them, and all the later authors rely heavily upon their teaching. Worth mentioning, though, is Abu'l-Qasim ibn Tawus (d. 1265), whose *Faraj al-mahmum* collected historical facts about astrology as well as the opinions of its upholders and opponents.

The determination of the astrological elements requires a good knowledge of astronomy, and since rulers wanted to secure important decisions by asking the scholars at their court for their advice, we find that many astronomers were also, *per amore o per forza*, astrologers (even Kepler resorted to astrology for income). We find thus among astrologers prestigious names like those of al-Battani, al-Biruni and al-Tusi.

Alchemy

The main roots of Arabic alchemy *(al-kimiya')* are to be found in the Hellenistic authors known as Hermes Trismegistus and Apollonius of Tyana. From Greece, the Arabs inherited the basic distinction into four elements (earth, water, air, fire), by the combinations of which all other substances may be formed; the existence of four qualities (hot, cold, moist, dry), the proportions of which characterize the features of the substances and which are, for metals, always present and separated into two pairs, one external and one internal (gold being, for example, warm and moist outwardly and cold and dry inwardly, the opposite for silver); the importance attributed to mercury and sulphur, the liquid metal and the burning stone, which embody the properties of being cold and moist, and warm and dry respectively.

Islamic alchemy finally inherited the principal aim of seeking to transmute base metals into precious ones, particularly gold, by means of heating, mixing, corroding, colouring, or using an elixir (*al-iksir*, from the Greek ξήριον, a desiccative powder used for wounds), the aim of all these manipulations being the acceleration of the slow natural process of transformation of any metal to gold in the earth. A few (like Ibn Sina, who also opposed astrology) thought that such operations could at most produce similarity and not identity.

The best-known Arabic alchemist is Jabir ibn Hayyan, the Latin Geber, who flourished in the second half of the eighth century, and to whom is attributed a whole corpus of writings which in fact was completed during the following two centuries; he was of course familiar with the operations of evaporation, distillation, calcination, sublimation, fusion, filtration and crystallization, and knew how to prepare arsenic and antimony (his *Summa perfectionis magisterii* was first printed in Rome in 1485). Alchemy became closer to chemistry with al-Razi (c. 860–930), the Latin Rhazes or Rasis, a Persian from Rayy (near Tehran), who was trained in Baghdad and then assumed directorship of Rayy's hospital, where he wrote the famous medical book *Kitab al-hawi* (*liber (totum) continens*, first printed in Brescia in 1486). His works on alchemy (the most important of which is the *Kitab al-asrar, liber secretorum*) are characterized by the importance attached to experiments; thus, he describes carefully the chemical processes mentioned above, how to obtain caustic waters, and various apparatus, some of which, although of Greek origin, are recorded in modern European languages in their Arabic form (*aludel, alembic* – not to mention the Arabic article in *alchemy*). His influence is seen in a work on alchemical apparatus written by al-Kathi in Baghdad in the early eleventh century, which was translated into Persian. At that time, alchemy was not cultivated solely in the east: the latin *Picatrix* is translated from an Arabic text by al-Majriti (early eleventh century – different from his namesake mentioned in the section on astronomy, above). Another translation from the Arabic, widely spread in the Latin world, was the *Turba philosophorum*, a compilation of Greek sources of uncertain date and origin recording a sort of congress of Greek alchemists belonging to various schools and to various centuries.

The theory of alchemy may have been basically wrong and its goal illusory. Nevertheless, its experimental side helped to improve industrial technique, such as refining metals, dyeing cloth and leather, colouring, glueing, manufacturing ceramics and glass, preparing soaps and perfumes (obtained from plants mixed with water by distillation, whereas antiquity simply mixed them with oil), developing the refining processes of sugar and the preparation of candies, producing paper (transmitted to Europe in the twelfth century), discovering – both for alchemical and medical purposes – 'elixirs', and finding new combinations of elements.

Zoology

The study of animals (*hayawan*) has its roots in the pre-Islamic period, and the rich lexicon includes early and dialectical varieties used to designate animals, in particular domestic animals and above all camels and horses. Although the Arabs inherited the Aristotelian corpus, their zoology seems not to have led to scientific research so much as to have inspired literature and art, and that type of curiosity which led to the formation of impressive zoological collections. Zoology, it seems, was motivated solely by practical needs; thus its objects were, for domestic animals, husbandry, breeding, diseases and their cure, and, for mankind, therapeutics (or poisons) by means of animal products and the magical properties of them, as described in the *Liber sexaginta animalium* by Rhazes, extant only in a Latin translation. Another aspect arose from the tie between religious rituals and certain animals, the former forbidding either selling or consumption (or both) of the latter.

The first comprehensive early work, completed before 850 by al-Jahiz, describes several hundred animals, in and around the region of Iraq, with occasional notes on their diseases and how to cure them. Large sections on animals are found in the epistles of the fraternity called *Ikhwan al-Safa'* (Brethren of Purity), an account of all the sciences written in the tenth century. Among philosophers, Ibn Sina was the author of a compendium of Aristotle's *Historia animalium*, a Latin version of which, the *Abbreviatio Avicenne de animalibus*, was made for Frederick II of Hohenstaufen (printed c. 1500 in Venice), and Ibn Rushd wrote commentaries on Aristotle's *De generatione animalium* and *De partibus animalium*. From the thirteenth century onwards, we encounter various encyclopaedic works containing specific parts devoted to animals; such is the case for the celebrated *Cosmography* of al-Qazwini (d. 1283) or the encyclopaedia by al-Nuwayri (1279–1333). But the most complete study on zoology of the Islamic world is the late fourteenth-century *Life of the animals* by al-Damiri, a compilation of earlier sources extant in numerous manuscripts.

These are some of the most notable treatises. Others depend more or less upon them, adding observations, lexicological remarks, and quoting sayings or proverbs. As a consequence of observed or reported facts, and the influence of

tales involving animals (like the *Kalila wa-dimna* translated from the Sanskrit into middle Persian around 550 and two centuries later into Arabic), we often find observations about animal psychology. There are also more specific treatises, most commonly about horsemanship or the use of domestic animals for hunting; the work on falconry by Frederick II, *De arte venandi cum avibus* (an incomplete edition published at Geneva in 1560, first complete edition Augsburg 1596) had Arabic sources, which themselves have Greek foundations. Many of the zoological manuscripts are beautifully illustrated.

Although zoology was more concerned with observation and practicalities than with the classification of species and establishing connections between them, we do find some divisions into categories. Thus, al-Jahiz divides animals into four categories according to the way they move: walking, flying, swimming, crawling. His subdivisions follow more subjective than objective criteria, the highest category of flying animals, for example, consisting of eagles and vultures, which are carnivorous and able to defend themselves. This latter quality is held by al-Qazwini for his own classification, for he groups animals according to the means they use for their defence: first comes their strength, then their ability to flee, next their passive defence (such as the hedgehog), lastly their capacity to find a natural refuge. One may also remark the attempt found in the *Ikhwan al-Safa'* of establishing a hierarchy of animals, ranging from the lower level of the snail, just above plants, to the upper one of monkeys and elephants, just below humans; the interest in border elements has always received particular attention from philosophers, from the Greeks to evolutionists such as Charles Bonnet in his *Palingénésie*.

Mineralogy

Arabic knowledge of mineralogy is inherited, as with other sciences, principally from Greece, but depends in part upon Persian and Indian sources. It is mostly known in Arabic as the science of 'stones' (*ahjar*), although the term 'stones' may not be considered appropriate, since it extended to anything which did not belong to the categories of animals or plants. Stones were considered mainly for their material value or usefulness, but occasionally also for their medical or magical properties, linking mineralogy to alchemy, medicine and astrology. Among texts or writers on mineralogy one finds some names already met in zoology: al-Jahiz, the *Ikhwan al-Safa'*, al-Qazwini. The most important studies are, however, those by Ibn Sina and, more specifically on precious stones, by al-Biruni. Treatises are also found in the twelfth and thirteenth centuries, and the tradition continues until modern times, both in Arabic and other languages. Worth mentioning is a treatise written by al-Tusi in Persian at the request of Hulagu.

Besides the description and grouping of stones according to their aspect (colour, texture) and their weight, one finds attempts to classify them according to their reaction to heat, their uses, or to their solidity (which is reminiscent of

Theophrastus). Thus, Jabir ibn Hayyan distinguishes three types: spiritual, which evaporate under the action of fire; metallic, which liquefy, can be bent, may be made bright by polishing and may resound; and mineral, which may or may not melt, but cannot be bent and will crumble. Ibn Sina, who chooses solidity as the criterion, distinguishes between stones, sulphurs, salts and fusible substances. One finds also more subjective criteria: al-Jildaki (early fourteenth century) distinguishes between gems, mineral stones, fabulous stones, magnetic stones, and stones found in animals.

Deficient as the theory of classification may have been, it did not prevent notable results being attained, both experimental and theoretical. Al-Khazini, who (following earlier attempts by al-Asfizari) invented an extremely accurate balance, the *balance of wisdom*, wrote a treatise on it in which he established a table of specific weights of a number of metals (such as gold, silver, lead, copper, iron, tin, mercury), of glass, salt, blood, and of some precious stones and special earths; the quantities he arrived at are often remarkably close to modern values. Before him al-Biruni (whose specific weights are relative to that of gold) concluded, during a stay in India, from the forms of the stones in the plain of the Ganges, that it was once covered with water. Earlier still, the *Ikhwan al-Safa'* rightly identified fossils as the petrified remains of marine animals, and concluded that there had been changes in the level of the sea (that fossils were remains of organisms was already maintained by Greek and Latin writers, but they were considered as fanciful creations of nature by Aristotle).

Botany

The roots of botany in the Islamic world are again partly Greek (pseudo-Aristotle's *De plantis*, Dioscorides, Theophrastus), and partly inherited from local observations and traditions (note that for instance Roman authors were influential in agriculture in Islamic Spain). Like other natural sciences, botany cannot be said to be a separate science in the Islamic world. Thus, information about plants (*nabat*) is found in encyclopaedias, in dictionaries, in treatises on pharmacology and medicine (healing virtues, dietetics), on agriculture (sowing time, pruning), and on magic or astrology (fanciful ways of improving production). One of the most influential writings was Ibn Wahshiyya's *Nabatean Agriculture*, a (sometimes contrived) compilation from earlier sources written in the ninth century. Abu Hanifa al-Dinawari's contemporary *Book of Plants* is a thorough study: plants are considered in groups, according to their qualities or uses, and afterwards also in alphabetical order. In the tenth century, chapters on plants appear in the *Ikhwan al-Safa'*, and later in Ibn Sina's writings; in both cases, the dependence on the *De plantis* is obvious. As is the case for zoology (to a lesser extent mineralogy), many manuscripts are beautifully illustrated.

Classifications of plants follow various criteria. They may depend, as for al-Dinawari (who depended on Theophrastus), upon a plant's preservation through

the winter (either both root and stem are kept, or only the root, or none), or upon plant's autonomy during the growth (they need a support in order to grow in height, or they do not, or they naturally expand in width in the soil). Trees are often distinguished, for instance by the encyclopaedist al-Nuwayri, by the characteristics of their fruits (they have neither rind nor stone, like apple and pear, or only a rind, like lemon and orange, or only a stone, like date and apricot). As in Greek science, the borderlines between animals and plants on one side, between minerals and plants on the other, received particular attention from philosophers.

With the same insight he had shown in geology, al-Biruni inferred from the change in vegetation the occurrence of a climatic change; he found near Kirman remains of palm-trees, which pointed to a locally warmer climate in the past. Ibn Sina noted that the appearance of a plant may vary according to its geographical situation.

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Chapter Four

Incunables and Sixteenth-Century Books

Sachiko Kusukawa

In the period under consideration in this chapter (c. 1450 to 1600) a new technology, the (hand-pressed) movable-type printing press, appeared and became established as a means of book-production in Europe. Books printed before 1501 using this technology are commonly classified as *incunabula* ('swaddling clothes'), a term first applied in 1688 to books produced during this nascent period of printing.[1] For its historical as well as antiquarian value, this class of books has frequently received special treatment and detailed documentation. The standard catalogues of *incunabula* are: L. Hain, *Repertorium Bibliographicum ... ad annum MD* (Stuttgart and Tübingen 1826–91, 5 vols), supplemented by W.A. Copinger (London 1895–1902, 3 vols) and further by D. Reichling (Monaco 1905–14, 8 parts); F.R. Goff, *Incunabula in American Libraries: the third census* (New York 1964; with supplement, New York, 1972) and *Gesamtkatalog der Wiegendrucke* (Leipzig 1925–, 9– vols).[2] Most major libraries, including the British Library (R.G.C. Proctor, *An Index to the Early Printed Books in the British Museum*, London 1898–1903, 4 vols) have also published catalogues of their own *incunabula* holdings. More importantly, there is now an international project to list *incunabula* on electronic medium (ISTC), which is accessible via the BLAISE-Line.

For books printed in the sixteenth century, the *Index Aureliensis* (Baden-Baden 1964–, 11– vols) aims at comprehensive coverage of all books printed in the sixteenth century. It is still, however, at 'Des'.[3] Although the following do not aim at such comprehensive coverage, their listings are quite extensive: *Verzeichnis der im Deutschen Sprachbereich erschienenen Drucker des XVI*

NICOLAI
COPERNICI TO-
RINENSIS DE REVOLVTIONI-
bus orbium cœlestium,
Libri VI.

IN QVIBVS STELLARVM ET FI-
XARVM ET ERRATICARVM MOTVS, EX VETE-
ribus atque recentibus obseruationibus, restituit hic autor.
Præterea tabulas expeditas luculentasque addidit, ex qui-
bus eosdem motus ad quoduis tempus Mathe-
matum studiosus facillime calcu-
lare poterit.

ITEM, DE LIBRIS REVOLVTIONVM NICOLAI
Copernici Narratio prima, per M. Georgium Ioachi-
mum Rheticum, ad D. Ioan. Schone-
rum scripta.

Cum Gratia & Priuilegio Cæs. Maiest.

BASILEAE, EX OFFICINA
HENRICPETRINA.

Liber Collegij Corporis Christi

2. Copernicus *De revolutionibus*, second edition (1566).
Reproduced courtesy of Bernard Quaritch Ltd.

Jahrhunderts (Stuttgart 1983–95, 24 vols), commonly known as 'VD16', lists the holdings of the two richest collections of German imprints,[4] the Bayerischen Staatsbibliothek, Munich, and the Herzog August Bibliothek, Wolfenbüttel; the late Brigitte Moreau's *Inventaire chronologique des éditions Parisiennes du XVIe siècle* (Paris 1972– , 4– vols, to 1535), is an indispensable list of Parisian imprints ordered chronologically;[5] the *Catalogo collectivo de obras impresas en los siglos XVI al XVIII existentes las bibliotecas españolas* Seccion I. Siglo XVI (Madrid 1972–84, 15 vols) contains many rare sixteenth-century items; H.M. Adams, *Catalogue of Books printed on the Continent of Europe 1501–1600 in Cambridge Libraries* (Cambridge 1967, 2 vols) lists, in addition to the University Library collection, holdings of Cambridge colleges and departmental libraries which are otherwise relatively difficult to establish; the catalogue of Oxford Bodleian Library is now available on CD-ROM and through the Internet. Holdings in the Vatican Library may be found on Eureka-RLIN (Research Libraries Information Network, North American database). Although an increasing number of library holdings are becoming available through the Internet (though some only by subscription), it is necessary to check the daily, variable state of retrospective cataloguing in each case.[6]

While chronologically qualified catalogues have their advantages and uses, the incunabula/post-incunabula distinction is not always useful for an overview of the development of the printed book over the period up to 1600. The *Short Title Catalogues* of the British Library, grouped by country of publication, are more helpful in this respect since they list all books from the beginning of printing through to 1600. More specialized catalogues of printers may provide a more detailed picture of the development of individual cases over time, such as those of the Aldine Press (which printed numerous *editio princeps* of classical authors), the Petreius Press (printer of the *De revolutionibus* and other mathematical works), the Cavellat/De Marnef Press (which had a heavy concentration on mathematics and astronomy books) and the Wechel Press (which printed works of Pierre de la Ramée and Jean Fernel).[7] It is always important, however, to keep in mind the extent of coverage and conditions imposed upon each catalogue in order to find most expeditiously the relevant information.

Focusing on the history of science, A.C. Klebs compiled a short-title list for incunables in 1938, which was further analysed by Sarton.[8] Stillwell's list, which is based on Klebs's but continuing up to 1550 (with an emphasis on first editions), includes useful references to secondary literature on the book or subject in question.[9] More recently, the extensive collection of scientific and medical books at Herzog August Bibliothek has been listed in a separate catalogue, as has the collection at the Newberry Library, Chicago.[10] The lists of Zinner and of Houzeau/Lancaster are extensive and still very useful for astrological and astronomical imprints, though neither provide location of printed books, while Grassi does.[11] LaLande's compilation has the merit of chronological listing of titles.[12] It should be remembered that catalogues of libraries famous principally for their medical collections may be equally helpful since they tend

to include books on other subjects such as mathematics, astronomy, and studies of plants, animals and minerals.[13] There are many other potentially useful catalogues, which focus, for instance, on printed books containing illustrations[14] Other specialized book-lists will be mentioned in their relevant sections.

The diffusion of movable-type printing presses did not mean, however, that the printed book immediately superseded manuscript culture. Indeed recent scholarship has shown how manuscript culture coexisted side by side with the printed book.[15] Richly illustrated, printed copies of Pliny's *Natural History* or of Aristotle's *opera*, or a copy of Euclid's *Elements* printed on vellum with a dedication in gold ink, are cases which exemplify how early printed books functioned like the manuscript book.[16] Instances like that of Thomas Linacre (c.1460–1524), who had a manuscript copy made of his translation of Proclus' *Sphaera* (printed already by Aldus Manutius in 1499) for a dedication copy, also indicate that hand-written scripts could retain an aesthetic and economic value above that of the printed text.[17] At the lower end of the market there also continued to be a thriving traffic of copied and re-copied handwritten lecture notes among students. Handwritten private letters (often intended for wider circulation among friends), furthermore, were important means by which dried plant specimens, seeds, bulbs, ancient coins, instruments and ideas were exchanged. Manuscript culture, as existing alongside the printed book, is therefore an important, but on the whole still untapped source for the history of science.

For information on manuscripts during this period, one cannot do better than start with Kristeller, on whom Jayawardene based his selection of catalogues of scientific manuscripts.[18] The Wellcome Institute Library, London, holds an important collection of manuscripts.[19] There are also several lists of manuscripts with disciplinary qualification: Zinner's is the most comprehensive list for astronomical and astrological manuscripts in the German-speaking area; Lindberg has gathered a selection of optical manuscripts; some fifteenth- and sixteenth-century Latin manuscripts of Arabic astronomy and astrology have been listed by Carmody; the list by Thorndike and Kibre includes in general manuscripts up to 1500 and alchemical manuscripts to the end of the sixteenth century; Lohr's compilation can also be used to locate manuscripts of Aristotle commentaries; Hankins, on the other hand, has produced a census of (fifteenth-century) manuscripts of Latin translations of Plato.[20] Another important manuscript source is the annotations in the printed book itself, which the British Library have catalogued separately.[21] For locating extant correspondence, *Iter Italicum* is a good starting point, especially now with its CD-ROM version which expedites searches for a combination of names and keywords.[22]

Printing technology, furthermore, should not be considered simply as a neutral medium linking author and the reading public. The printed book was a product of printers who were concerned as much with profit-making, beating competition and building reputation, as they were with the content of a book. It is true that there were some printers who were committed to promoting particular intellectual programmes – Aldus Manutius, for instance wanted to revive

and disseminate the knowledge of Greek and Latin and the works of classical authors.[23] There were others like Cavellat, who economized on reprinting the same textbook by producing title pages with future or multiple years of publication.[24] And there were those like Wechel, who deliberately flooded the market with editions of textbooks by Pierre de la Ramée in order to retain monopoly of these titles.[25] This suggests, of course, that a high frequency of printing a particular title does not necessarily translate into its popularity among the reading public.

It should be remembered that printers had to make a living: they ran an establishment of inkers, pressmen, typesetters, and correctors; they often functioned as bookseller, binder, paper-supplier or agent for other printers as well; they hired journeymen to sell their books; they found investors and underwriters for their enterprise; and they often went to court for disputes over payment and other troubles.[26] A printed book was thus a commodity produced to make a profit and, as such, it was also an object worth protecting against local competitors. Printers and sometimes authors and editors procured privileges for the sole right to publish a particular title or groups of books. These privileges forbade other printers to print or sell the title in question within a given territory for a number of years and stipulated financial penalties against transgressors. They were first sought by printers and editors in fifteenth-century Venice.[27] Printers in Germany began to procure privileges from the Holy Roman Emperor in the sixteenth century, while French printers sought privileges from the royal chancery or the Parlement of Paris.[28] Papal privileges were sought not only by printers in Rome and the Papal States, but also by printers in Germany and Italy. In order to get round this practice of privileges, authors and printers alike produced variant or emended texts under the same titles or simply commissioned printing outside the jurisdiction of the privileges. It is necessary to remember, therefore, the printer's role in producing variant texts for different editions of a title.

Parallel to protecting the right to print certain titles by printers and authors, some authorities, such as the Venetian Council of Ten, began to check the content of book when granting privileges. The first call for censorship came in 1470 from a humanist-author concerned to protect the integrity of Pliny's work (see below, p. 125). In 1479, Sixtus IV granted the right to the University of Cologne to censor printed books and in 1485 the Archbishop of Mainz, Berthold von Henneberg, authorized censorship by professors of the Universities of Mainz and of Erfurt to censor all vernacular translations from Greek and Latin titles, with penalty of excommunication, fine and confiscation of books, if transgressed. Despite repeated warnings of the misuse of printing and the increase in granting censorship rights, no sense of urgency to regulate the content of books arose until it became clear that efforts to unite the Protestants and the Roman Catholics had irrevocably broken down. Systematic legislation of censorship came in place in Milan, Venice and the Papal States around 1540s with locally produced indexes of prohibited titles. The mechanism for enforcement became

more effective with the Roman Inquisition.[29] On the other hand, Martin Luther himself petitioned the Duke of Saxony to prohibit books by Karlstadt and was also responsible for instigating the closure of the press of the Brothers of the Common Life in Rostock (1530).[30] In France, the faculty of theology at the Sorbonne, bishops and the ecclesiastic courts, the King and his Conseil, and inquisitors of faith all had the right to censor the content of books.[31]

Despite such efforts to protect the printing, as well as regulate the content, of books, printed books were not necessarily confined to function as a means for disseminating ideas or providing information. Some books were meant to be destroyed and to be made into something else – by cutting out pieces, gluing or stringing them together and assembling them as an instrument or a device. Other books would not have made sense on their own, since they were to be used alongside an instrument or a globe. Books were also sold as large, colourful, luxury items, and they were often used as gifts.[32]

The problem of defining a *scientific* book in this period, however, is an elusive one, since our definition and expectation of 'science' is markedly different from those of the past.[33] In the period between 1450 and 1600, *scientia* could broadly mean human rational knowledge (to be contrasted with *sapientia*, knowledge of the divine) or it could be taken in a stricter, Aristotelian sense of demonstrative knowledge of causes. *Scientia naturalis* or *philosophia naturalis* in universities usually meant the study of Aristotle's *libri naturales*, although there was a wide variety in the texts or parts of texts studied and the manner in which they were taught.[34] Mathematics could be considered a separate branch of *scientia*, or an *ars* (useful knowledge). Some, like Frederico Commandino, praised the certitude of mathematical demonstration without reservation while others like Alessandro Piccolomini thought that it was inferior to that of syllogistic reasoning. It was generally agreed, however, that mathematical reasoning could be applied only to certain other disciplines, namely to the 'middle sciences' (so-called because they were considered to be halfway between natural philosophy and mathematics) such as mechanics or optics.

The study of astronomical and planetary theories was considered important in this period because astrology constituted an integral part of professional medical prognosis and princely counsel. There were many other disciplinary connections which may seem alien to the modern eye: plants, animals and gems were studied for their medicinal virtues; contemporary knowledge about chemical reaction could be found in distillation and alchemical manuals; commentaries on Avicenna's *Canon* could contain comments on Copernicus, and Vesalius' anatomical findings were used in commentaries on Aristotle's *De anima* and on the *Posterior analytics*.[35] Alongside such university learning, which was conducted and written in Latin, there were many other activities which occurred outside the universities, such as fortification, ballistics and 'abacus' arithmetic, in which new and sophisticated understanding of nature or of mathematics was presented, often in the vernacular. The great mobility of careers and overlapping of several occupations further meant that people may not have been making a

living out of, nor indeed held a professional identity in, the area of expertise for which they are known today.[36] Trying to locate 'first' successes in history of science according to our modern criteria of science, therefore, would hardly do justice to the variety and richness of the books of this period.[37]

My aim in this chapter instead has been to cast a net as widely as possible to include material which seems to me to describe or understand (in the most general sense) the workings of nature, machines and mathematical ideas. One area which is not covered here, however, is the area of medicine which has been dealt with in the companion volume. Even this decision results in a strange selection according to sixteenth-century standards: a part of the *materia medica*, the study of plants, will be excluded, but another part, the study of gems, animals and birds, will be discussed here; and astrological manuals (which often had medical uses), will also be included in this chapter. While I fear an overview of this kind will always entail somewhat arbitrary selections and omissions, I hope that references to catalogues and secondary literature in the notes will guide readers towards locating further information.

Aristotelian publications

The *scientia naturalis* taught in the arts faculties in the universities of this period consisted mainly of studying Aristotle's *libri naturales*. The dominance of Aristotle as an authority on natural philosophy is indisputable from the fact that for the period from the beginning of printing to 1600, it is estimated that around 4000 editions of *Aristotelica* were printed, compared to under 500 for *Platonica*.[38] Here I offer a rough overview, as it will be impossible to deal with the entire corpus of Aristotelian imprints.[39]

The format of Aristotelian imprints varied considerably: from the Greek text of the entire *opera* in large folio tomes (Venice: A. Manutius, 1495–98, 5 vols, *editio princeps*) to the small octavo textbooks which summed up the whole of the *libri naturales* in one book. The range included Latin translations of one or more of Aristotle's books, parallel texts in Greek and Latin,[40] vernacular translations, texts with commentaries, commentaries without texts, excerpts and paraphrases, compendia and summaries.

In general, all texts of Aristotle were available by 1500,[41] including pseudo-Aristotelian texts: the *Secreta secretorum* first appeared in 1472 (Cologne: A. Holruen), and was last printed in 1555 (Naples: F. Storella);[42] the *Physiognomia* was included in the Aldine Greek edition and in the Latin *Opera* of 1482 (Venice: P. Petri); the *Theologia* became available in print in 1519 (Rome: J. Mazochius).[43] The *Mechanical problems* in particular received closer study than ever before. It was translated into Latin first by Vittore Fausto in 1517, which was then superseded by a translation and commentary by Niccolò Leonico Tomeo (1456–1531) in his *Opusucula* of 1525 (Venice: B. Vitalis).[44] Alessandro Piccolomini (1508–79) wrote a paraphrase, the *In Mechanicas Quaestiones*

Aristotelis Paraphrasis in 1547 (Rome: A. Blado), which was translated into Italian by Vannoccio Biringuccio in 1582 (Rome: F. Zanetti). Niccolò Tartaglia (1499/1500–57) discussed the *Mechanical Problems* in books VII and VIII of his *Quesiti et inventioni diverse* (Venice: V. Ruffinelus for N. Tartaglia, 1546). Girolamo Cardano (1501–76) commented on several of the *Mechanical problems* in his *Opus novum de proportionibus* in 1570 (Basle: H. Petri). The teaching of the *Mechanical problems* was a sixteenth-century phenomenon: it seems that Pietro Catena (d. 1577) was the first in Italy to lecture on the *Mechanical problems* in his mathematical lectures at Padua.[45] His successor was Giuseppe Moletti (1531–88), whose lecture notes survive.[46] Galilei occupied Moletti's chair between 1592 and 1610, and is known to have lectured on the *Mechanical problems* in 1598.[47]

Although Aristotle's works were available in print in the Latin translation from the Greek by Johannes Argyropulous in 1479 (Augsburg: A. Keller, 4 vols), the printing of Aristotelian works up to 1520 was dominated by medieval Latin texts and the works of their medieval Latin and Arabic commentators. For instance, William of Moerbeke's translation of the *Physica* appeared in 1475 (Louvain: K. Braem), of the *Meteora* (Venice: L. Canozius) in 1474 with four more editions before 1500 and of the *De caelo et mundo* in 1473 (Venice: L. Canozius) with three more incunabula editions; Albertus Magnus' commentary on the *De animalibus* appeared in 1478 (Rome: S. Chardella) and Albert of Orlamünde's introduction to the *libri naturales* (often attributed to Albertus Magnus), the *Philosophia pauperum*, went through many printings from 1480 (Toulouse: H. Mayer for J. Schilling) onwards; Thomas Aquinas' commentary on the *Physica* first appeared in Genoa (M. Moravus) between 1474 and 1480; Johannes Duns Scotus' *Quaestiones super libros de anima* in 1490 (Pavia: A. de Carcano); Johannes Versor's *Quaestiones super VIII libros physicorum* appeared with the text in 1489 (Cologne: H. Quentell); William Ockham's *Summulae in Physica Aristotelis* was printed in 1494 (Bologna: B. Hectoris Faelli); and a commentary on William of Heytesbury's *De motu locali* appeared in 1484 (Pisa: G. de Gente).[48]

This was also a period of a printing revival for the commentators of Aristotle. A revival of Averroës' commentaries was centred in Venice and at the University of Padua: the *Organon* was not included in Lorenzo Canozio's edition of Averroës (Padua, 1472–7), but was included in Nicolas Vernia's edition of 1483, which in turn served the basis of the great 1550–52 Giunta edition.[49] Works by Greek commentators of Aristotle were also duly printed: Simplicius' *Hypomnemata in Aristotelis categorias* was published in 1499 (Venice: Z. Kallierges for N. Blastos); Alexander of Aphrodisias' commentary on the *Problemata* in 1488 (Venice: A. de Strata) and on the *De anima* in 1495 (Brescia: B. Misinta); Themistius' *Paraphrasis in Aristotele* appeared from 1481 (Treviso: Confaloneris et Gerardinus).[50]

The Parisian reformer, Jacques Lefèvre d'Étaples (c.1460–1536), is generally credited with initiating the move away from the scholastic *quaestio* format by

using paraphrases and running commentaries, beginning with his *In Aristotelis libros naturales introductiones* (Paris: J. Higman 1492). From 1535 onwards, humanist commentaries which quote passages in Greek or explain Greek terminology become prevalent, such as those by Julius Pacius (1550–1635), Benito Pereira (1535–1610), Agostino Nifo (1469/70–1538) and Philip Melanchthon (1497–1560).

The availability of Greek texts and Latin translations from Greek, however, did not necessarily imply a transformation of a philosophical culture which was founded on concepts and terminology of the medieval Latin editions. This is particularly true of the *De anima* commentaries.[51] Johannes Argyropulos' translation of the *De anima* from the Greek utilized the philosophical terminology developed by William of Moerbeke in the thirteenth century, and it was the latter's Latin edition upon which most commentaries of this period, including the one by Jacopo Zabarella (1533–89), were based (Venice: F. Bolzetta, 1605). Some commentaries, such as those of Thomas Aquinas (Venice: heirs of O. Scotus, 1507) were accompanied by the double Latin texts of Moerbeke and of Argyropulos. It was Benito Pereira (d. 1610) who made an effort to 'Ciceronianize' the text, to the extent that it was entitled *De animo* (Paris: T. Richardus, 1549), but few commentaries appeared using this text.

From 1550 onwards, a philosophical reaction to an excessively philological approach of the humanists was reflected in the Italian output of *Aristotelica* which focused more on the commentary of medieval authors and contemporary university teachers, while North of the Alps, Paris became the centre for publishing new Latin translations and Greek texts of Aristotle.[52]

Another major characteristic from the mid-sixteenth century onwards is the appearance of 'textbooks', mostly octavo in size, and specifically designed for classroom use. These usually offered a summary of arguments across several books of the *libri naturales*, and expounded upon Aristotle's philosophy through topics rearranged for didactic clarity, and supplemented areas Aristotle had not written on, such as optics, astronomy and botany.[53] The philosophical textbook appeared both in Protestant and Catholic territories, authored by men such as Franciscus Titelman (1502–37), Philip Melanchthon, Benito Pereira, Georg Liebler (1524–1600) and John Case (1546–1600).[54] In this genre there was scope to include material alien to Aristotle and to re-examine the foundations and the subject-matter of natural philosophy.

One area in which the classicizing efforts of the humanists had made their mark in the university studies of Aristotle was the area of logic textbooks. The dialectic manuals of Lorenzo Valla, Rudolph Agricola, Johannes Caesarius and Philip Melanchthon began a tradition of textbooks which incorporated the topical and rhetorical traditions, as well as the traditional syllogistic and demonstrative arguments. They offered a wider range of tools for arguments – such as the orator's skill to argue in *utramque partem* – which were not necessarily demonstrative or rigorous. Risse has produced an exhaustive list of logical and dialectical manuals of this period, accompanied by a descriptive study of

their contents.[55] Recent scholarship has shown how such humanist dialectics and rhetoric constituted important elements in the works of Francis Bacon and Galileo Galilei.[56]

At the end of the sixteenth century, scholastic forms of Aristotelian commentaries were revived (with the Latin texts of Argyropylos) in the series of commentaries initiated by Pedro da Fonseca (1528–99), and issued by the Jesuits at the University of Coimbra (the *Commentarii Conimbricenses*, 1592–98). The reaffirmation of the authority of Aquinas at the Council of Trent further led to a revival of Aquinas publications in the 1550s and 1560s, which was unique for a medieval author.[57] Galilei, for instance, had a solid understanding of this kind of natural philosophy taught at the Jesuit *Collegio Romano*.[58] It would be wrong, however, to assume that Catholic commentators exhibited a uniform and monolithic tradition of following Aristotle and Aquinas.[59]

Platonic and neo-Platonic publications

Such active and varied publication of Aristotle's corpus was accompanied by the publication of many other classical authors who had written about nature and the mathematical sciences. The works of Plato had an appeal to humanists for several reasons: for advancing their own literary careers, teaching ideal political systems and as works of a classical author whose views were closer to Christianity than Aristotle's.[60] Plato's works were translated into Latin by Marsilio Ficino (1433–99) and published for the first time in 1484 (Florence: L. Venetus, apud S. Jacobum de Ripolis). The Greek text was first printed in 1513 by the Aldine Press.[61] Platonic and neo-Platonic philosophy became widely known through the writings of Ficino, who was also the central figure at the Platonic Academy in Florence.[62] Ficino believed that Platonic philosophy was in harmony with Christianity and sought to establish a new theology on the basis of the belief that there existed a long tradition of 'ancient theology (*prisca theologia*)' from the time of Moses which prefigured Christianity.[63] This belief led him to study the wisdom of pre-Christian thinkers such as Plato, Plotinus and Proclus. He was commissioned to translate the works attributed to Hermes Trismegistus (a mythical Egyptian thinker then believed to be a contemporary of Moses) by Cosimo de' Medici (1389–1464), which was printed in 1471 (Treviso: G. de Lisa).[64]

Albeit sporadically, Plato's works began to be taught in the universities in the sixteenth century.[65] It is known that at the University of Paris, Jerome Aleander (1480–1542), Professor of Greek, first taught Plato's works between 1508 and 1515 and Adrian Turnebe (d. 1565) taught Plato's dialogues in 1547. The *Republic* was taught by Francesco Barozzi (1537–1604) as part of a mathematical course at Padua in 1560, and by Francesco Patrizi da Cherso (1529–97) at the University of Ferrara from 1578. From 1591/2 to 1597, Patrizi was professor of Platonic philosophy at the *Sapienza*, Rome, and lectured on the *Timaeus*.

Plato's works were translated into French by Louis Le Roy (1510–77): *Le Timée* (Paris: M. Vascosan, 1551); *Le Phédon* (Paris: S. Nyvelle 1553); and *Le Sympose* (Paris: L. Longis et R. L. Manguyer, 1558).[66]

Neo-Platonic works also appeared in print. Publication of some neo-Platonic authors, however, was identified with supporting flagrant paganism. In the 1460s for instance, publication of Macrobius planned by Andreas Bussi for the printers Sweynheym and Pannarz was cancelled for fear of incurring the wrath of Pope Paul II.[67] Macrobius' *In somnium Scipionis expositio* (Scipio's dream as described in Cicero's *De republica*, book vi) was eventually printed in 1472 by Jenson who had a close connection with Sweynheym and Pannarz.[68]

According to Houzeau/Lancaster, Proclus' *Hypotyposis astronomicarum positionum* was first printed in Latin (Venice, 1491).[69] Its Greek text, with a Latin translation by Georgius Valla, was printed in the 1540 Basle edition of Ptolemy's *opera*. The *Sphaera* by Proclus was translated by Thomas Linacre for the Aldine Press (1499). Jacobus Ceporini's scholia on the *Sphaera* appeared in 1523 (Basle: J. Bebel) with Dionysius Alexandrinus' *Orbis descriptio*, and Johannes Stöffler's commentary on the *Sphaera* appeared in 1534 (Tübingen: U. Morhard). The Greek text with Linacre's Latin translation appeared in 1547 (Basle: H. Petri).

Publications of other classical works

One of the earliest books to be printed in Italy was Pliny's *Natural History* (Venice: J. Speyer 1469). Many editions and printings followed, and the earliest call for censorship proposed to Pope Paul II came from Niccolò Perotti (1429/30–80), who wanted to protect the classics from incompetent editing (in this case a charge directed specifically against Giovanni Andrea Bussi's 1470 edition (Rome: C. Sweynheym & A. Pannartz) of the *Historia naturalis*).[70] Despite the severe attack on Pliny's reliability as an ancient authority in the works of Hermolao Barbaro's *Castigationes Plinianae* (Rome: E. Silber, 1493), and Niccolo Leoniceno's *On the Errors of Pliny and Others in Medicine* (Basle: H. Petri, 1529),[71] Pliny continued to serve as a source for astronomy (especially book two), medicine, natural history and many curious anecdotes throughout the sixteenth century.[72] Another Roman author whose works were printed frequently was Seneca: his *Opera* first became available in print in 1475 (Naples: M. Moravus) and 135 *incunable* editions of various works of Seneca are known. Along with Cicero's *De natura deorum* (Reggio Emilia: B. de Bazaleriis, 1495 onwards) Seneca's works served as a source for ancient Stoicism.[73]

Classical verses on nature also became available in print. Hyginus' *Poeticon Astronomicon* appeared in 1475 (Ferrara: A. Carnerius). Aratus' *Phaenomena* was first printed in Latin in 1474 (Brescia: H. von Cologne and S. Gallus) and the Greek text appeared with Julius Firmicus Maternus' *De nativitatibus* in 1499 (Venice: A. Manutius). These inspired contemporary poems such as

Giovanni Gioviano Pontano's *Urania seu de stellis libri quinque* (Florence: P. di Giunta, 1514).[74] Astronomical and astrological poems became particularly popular in the last half of the sixteenth century in France.[75]

A classical verse on the atomic structure of the world, Lucretius' *De rerum natura*, was first printed in 1473 (Brescia: T. Ferrandus) and frequently reprinted thereafter.[76] Several Parisian (quarto) editions were printed for students in the mid-sixteenth century, followed by a successful 'pocket edition' (16mo) from 1546 (Lyon: S. Gryphius) onwards. The first critical edition, with scholarly notes, of the *De rerum natura* was produced by Denys Lambin in 1563/4 (Paris: P. Gaultier de Roville), with a long introductory letter to Charles IX, and each book dedicated to different eminent persons, such as Henri de Mesmes and Ronsard.[77] There are no editions printed in Italy after 1515 (second Aldine edition), possibly due to the Counter Reformation. No full vernacular translation of the *De rerum natura* is known up to 1600. The poems of Giordano Bruno (1548–1600), *De immenso et innumerabilibus*, *De triplici minimo et mensura* and *De monade numero et figura* (Frankfurt a. M.: J. Wechel & P. Fischer, 1591) were written in the style of Lucretius.

In the sixteenth century, Vitruvius was often cited as one of the classical authorities on mechanics.[78] His *De architectura* contained descriptions of clocks, machines and buildings, and explained the ideal harmonic relation between symmetrical and properly constructed buildings and the universe. It was edited by Sulpicio of Verona and first published in Rome (E. Silber, 1483–90) with Frontinus' *De aquaeductibus*. The 1511 edition (Venice: G. Tridino) of the *De architectura* was edited by Giocondo of Verona, and is known for its beautiful woodcuts.[79] Daniel Barbaro's translation, *I dieci libri dell'architettura*, of 1556 (Venice: F. Marcolini) was accompanied by illustrations by Andrea Palladio.

An important source for ancient scepticism, Sextus Empiricus' *Outlines of Pyrrhonianism* was studied in manuscripts by humanists in the fifteenth and early sixteenth centuries, and became widely available after its first publication by a sceptical humanist-printer, Robert Estienne, in 1562 (Paris).[80] Doubts and criticisms of existing knowledge had already been voiced earlier in the century, for instance by Henricus Cornelius Agrippa (1486–1535) in his *De incertitudine et vanitate scientarum atque artium declamatio* (1530, s. l.) and by Gianfrancesco Pico della Mirandola (1469–1533) in his *Examen vanitatis doctrinae gentium et veritatis Christianae disciplinae* (Mirandola: J. Maciochius Bundenius, 1520). The *Outlines of Pyrrhonianism*, however, was a source for a more radical and systematic examination of the epistemological foundations of knowledge in late sixteenth and seventeenth centuries.[81] It prompted critiques of scholastic method like the *Quod nihil scitur* (Lyon: A. Gryphius, 1581) by Francesco Sanches (1550/1–1623).[82]

The works of the medieval missionary and philosopher, Raymond Lull, which offered a system of logic, rhetoric, philosophy, metaphysics and theology, independent of Aristotle, were avidly studied, especially by humanists centred in Paris: Jacques Lefèvre d'Étaples, Carolus Bovillus and Bernado de Lavinheta

studied and promoted Lull's works for his mysticism, metaphysics and the *ars combinatoria*.[83] Since the first printing in 1480 (Venice: F. Petio) of the *Ars generalis ultima*, 28 further incunables and 148 editions in the sixteenth century are known.[84]

Classical texts which contained histories of disciplines and lives of philosophers were important for men such as Kepler as a source of disciplinary history and history of discoveries.[85] Diogenes Laertius' *Vitae et sententiae philosophorum* was first printed in a Latin translation by Ambrosius Traversarius in 1472 (Rome: G. Lauer) and 17 more incunable editions are known. Polydor Virgil's *De inventoribus rerum* was published in 1499 (Venice: C. de Pensis).[86] Plutarch's *Vitae illustrium virorum* was first printed in 1470/71 (Rome: U. Han) and 39 more incunable editions are known.[87]

The printing of these classical works reflect the then prevalent taste and passion for recovering classical culture. This 'humanist' passion took the form of hunting for manuscripts, asking friends to be on the look-out for them, purchasing them, borrowing and copying them, then restoring them with palaeographical and philological skills.[88] Such passions led to the formation of extensive libraries by the literary-minded elite. Giorgio Valla of Piacenza (1447–1550), for instance, included in his *De expetendis et fugiendis rebus* (Venice: in aed. Aldi for J.P. Valla, 1501) Hero's descriptions of machines and some theorems of Archimedes found in his own extensive collection of ancient manuscripts. Cardinal Bessarion, whose library became the basis for the *Marciana*, also lent many manuscripts from his collection to Johannes Regiomontanus.[89] As is well known, the humanist interests of Nicolas V (Pope: 1447–55) led to the formation of the Vatican Library.[90]

Particularly important for the recovery of ancient Greek mathematics was the collection and patronage of the Dukes of Urbino. Federigo da Montefeltro (Duke: 1468–82) was possibly the wealthiest prince in Europe in his time, and offered patronage to artists as well as astrologers like Paul of Middelburg.[91] His successors continued this tradition of providing patronage to artists and scholars, and a group of humanist-mathematicians associated with the Dukes have been labelled the 'Urbino School'. To this school belonged Frederico Commandino (1509–75), Guido Ubaldo Marchese del Monte (1545–1607), and Bernardino Baldi (1553–1602).[92] Commandino translated into Latin Apollonius' works from a manuscript in the Urbino library and dedicated the work to Duke Guidobalde of Urbino in 1566. He also translated into Latin Hero's *Spiritalium liber* and Eutochius' commentary on it from an Urbino manuscript in 1575 (Urbino: D. Frisolino). In 1588, he printed the *Mathematicae collectiones* of Pappus of Alexandria (Pesaro: H. Concordia). Bernardino Baldi made a Latin translation of Hero's *Automata* in 1576, and of the eighth book of Pappus' *Mathematicae collectiones* in 1577 and wrote a commentary on Aristotle's *Mechanical questions* (1581–82). Guido Ubaldo da Monte, whose father was created Marchese del Monte by Duke Guidobaldo II of Urbino in 1543, wrote the *Liber mechanicorum* (1577), drawing on the Greek manuscripts of Pappus. It is characteristic of this school that they shared an

enthusiasm for classical knowledge, for studying Greek manuscripts and for producing the best Latin translation by careful philological and technical analysis. In their dedications to the Dukes of Urbino or other nobilities, they frequently extolled the virtues of recovering pristine Greek knowledge. There were, however, different emphases and preoccupation among the Urbino School: while Commandino placed more emphasis on philological and technical exposition of the text, Guido Ubaldo del Monte in his *Liber mechanicorum* in 1577 (Pesaro: H. Concordia) was more interested in situating the study of mechanics within an Aristotelian hierarchy of disciplines.[93] An Italian translation of Del Monte's *Liber mechanicorum* was commissioned by the superintendent to fortifications of the Republic of Venice, Count Giulio Savorgnan, from Filippo Pigafetta, and was published as *Le mechaniche* in 1581 (Venice: F. di Franceschi).

The mathematicians of the School of Urbino were also interested in the Archimedian mechanical tradition.[94] William of Moerbeke's Latin translation of Archimedes' *Circuli Dimensio* and *Quadratura paraboles* first appeared in 1503, followed by another edition by Niccolo Tartaglia printed in 1543 (Venice: V. Ruffinellus for N. Tartaglia) which included in addition, Moerbeke's translation of *Equilibrium of Planes* and book one of *On Floating Bodies*. The Greek text of Archimedes' *Opera*, based upon a codex commissioned by Leon, the ninth-century mathematician, was printed in 1544 (Basle: J. Herwagen), with a Latin translation of Jacob of Cremona. In 1558 Commandino published a Latin translation of the works of Archimedes which included the *Circuli Dimensio*, *De lineis spiralibus*, *Quadratura paraboles*, *De conoidibus et spheroidibus*, and the *Arenarius* (Venice: P. Manutius).[95] Commandino edited Moerbeke's translation of *On floating bodies*, including the second book and with corrected proofs, in 1565 (Bologna: A. Benacii). In the same year, Tartaglia also edited rather imperfectly Moerbeke's translation of *On floating bodies* in Venice (C. Troianum de' Navò). Guido Ubaldo del Monte's *In duos Archimedis aequeponderantium libros paraphrasis* (Pesaro: H. Concordia) appeared in 1588. Bernardino Baldi, who was also historian to the court of Urbino, composed the *vite de'matematici* (not published until 1887) in order to honour the memory of his teacher, Commandino. This included the life of Archimedes.

Mathematical textbooks – geometry and arithmetic

From 1530 onwards, there was also a renewed interest in teaching mathematics in universities as an essential part of propadeutic studies for philosophy or as an integral part of liberal arts. At Paris, Carolus Bovillus, Oronce Finé, Jacque Peletier and Pierre de la Ramée wrote mathematical textbooks and taught mathematics.[96] Philip Melanchthon, Joachim Rheticus and Michael Stifelius promoted mathematical studies in German Protestant universities and schools. Christopher Clavius was responsible for promoting mathematical studies in the *Collegio Romano* and other Jesuit colleges.[97]

For printers like Cavellat, the university textbook market, though somewhat narrow, was a stable and reliable trade.[98] The standard textbook in geometry, Euclid's *Elements*,[99] was first printed in a Latin edition (the Campanus version based on Adelard of Bath's translation from the Arabic) in 1482 with diagrams by the Venetian printer Ratdolt, who boasted in his preface the beauty of his diagrams which required great skill. A Greek-Latin edition edited by Bartolomeo Zamberti (1473–?1539) appeared in 1505 (Venice: J. Tacuinus), including a life of Euclid by Zamberti. The 1509 edition (Venice P. de Paganinis), edited by Luca Pacioli (1445–1517), includes a report of his lecture on the fifth book of the *Elements* given in the Church of St Bartholomeo on 11 August 1508. A full Greek edition (*editio princeps*) edited by Symon Grynaeus (1494–1541) was printed in 1533 (Basle: J. Herwagen), with Proclus' commentary on book one of the *Elements*. Diagrams were inset in the text (rather than arranged in the margins) for the first time in this edition. The 1537 Latin edition (Basle: J. Herwagen) included a preface by Philip Melanchthon, which was frequently censored. A new Latin translation from the Basle Greek edition was produced in 1572 (Pesaro: C. Francischini) by Commandino (1509–75) and in 1574 an extensive commentary on it (*Euclidis Elementorum libri XV*, Rome: V. Accolti) was produced by the Jesuit Christopher Clavius (1538–1612). It was the first six books of Clavius' edition that was translated into Chinese for the first time by Matteo Ricci and Hsü Kuang-Chhi (1607).[100]

The first full Italian translation by Niccolò Tartaglia of the *Elements* was printed in 1543 (Venice: V. Roffinelli for G. de Monferra, Pietro di Facolo and N. Tartaglia). The first French translation (of the first six books) by Pierre Foscadel in 1567 (Paris: De Marnef and Cavellat) was unusual in that each book was dedicated to different eminent persons. A German translation (of the first six books) by Wilhelm Holtzman first appeared in 1562 (Basle: J. Kündig). The first full English translation was carried out by Henry Billingsley (d. 1606), a wealthy merchant and later Lord Mayor of London, who had studied both at Cambridge and at Oxford. It appeared in 1570 (London: John Day), containing sixty 'pop-up' shapes pasted on the page. This was the only full translation in English until Isaac Barrow's in 1660. John Dee's preface to this 1570 edition is noted for its eulogy of the utility of the mathematical sciences aimed at practitioners.[101] An Arabic translation of the *Elements* appeared in 1594 (Rome: Typographia Medicea).

The standard arithmetic textbook in medieval universities, Boethius' *Arithmetica*, was first printed in 1488 (Augsburg: E. Ratdolt).[102] This contained explanations of prime and composite numbers, proportionality, 'figurate numbers' such as linear, triangular, cubic and pentagonal, and a multiplication table up to ten. Johannes de Muris' abridgement of Boethius, *Arithmeticae speculative*, was printed with works of other authors in 1515 (Vienna: J. Singrenium for L. L. Alantsee). From the 1530s onwards, new contemporary arithmetic textbooks which included explanations of arithmetic manipulations and long calculations began to appear. Henricus Loritus Glareanus' *De vi arithmeticae*

practicae speciebus ... epitome (1539) was a Latin handbook on arithmetic, with explanations of Greek, Roman and Arabic notations and elementary operations with integers.[103] Reiner Gemma Frisius' *Arithmeticae practicae methodus facilis* first appeared in 1540 (Antwerp: G. Bontius) and 67 more editions were printed up to 1585.[104] Jodocus Willichius' *Arithmeticae libri tres* (Strasbourg: C. Mylius 1540) was written in a catechetical style. The Lutheran pastor Michael Stifelius (1487–1567) published the *Arithmetica integra* in 1544 in which he attempted a comprehensive theory of all rational and irrational numbers (as found in the *Elements*, book X).[105]

The 'abacus' tradition

Outside the universities there existed a distinctive vernacular tradition of arithmetic, known as the 'abacus' tradition.[106] It was taught in schools for future merchants, architects and cartographers. The 'abacus' books were short tracts of practical arithmetic, using Arabic numerals and many practical examples for book-keeping, calculating interests and transferring currency. Most tracts were published in Italy, where the 'abacus' schools had originated in the thirteenth century.[107] The *Treviso Arithmetic* printed in 1478 (Treviso: M. Manzolo) was a problem-solving manual written in the Venetian dialect, and aimed at merchants around Treviso and Venice whose business was rapidly expanding and becoming complex.[108] Many 'abacus' manuals, such as Luca Pacioli's *Summa de arithmetica* (Vinegia: P. de Paganini, 1494), included instructions on algebra, substituting the unknown quantity with 'cosa' or 'res', following the Arabic tradition. In such 'abacus' manuals, a variety of words (often abbreviated) were used to substitute for different degrees of polynomials. A solution to a particular form of a cubic equation (in modern terms expressed as $x^3 + ax = b$) was found by Pacioli's colleague at Bologna, Scipione del Ferro (1465–1526), whose student in turn passed that solution on to Niccolò Tartaglia, a *maestro d'abacus*, in a competition.[109] Tartaglia himself solved another particular form (in modern terms of $x^3 = ax + b$) of the cubic equation. Girolamo Cardano (1501–76), who learnt from Tartaglia his solution with a promise not to publicize it, offered in his *Ars Magna* of 1545 (Nuremberg: J. Petreius) a method of reducing all cubic forms to the simpler forms of Scipione and of Tartaglia, after learning that the latter was not the first to find a solution.[110]

In Germany similar *Rechenmeisterschulen* spread from Nuremberg (which had commercial relations with Italy), and with them the use of Arabic numerals and algebra. A manual for merchants by Johann Widman (1462–98), *Behende unnd hubsche Rechnung auff allen Kauffmanschafft*, 1489, included the operational signs '+' and '–'.[111] Calculation using roman numerals with counters, however, was also quite popular, such as the *Rechenung auf der Linien und Federen* (Erfurt: M. Maler, 1522) of Adam Ries (1492–1559), a successful *Rechenmeister*, and the *Rechenbüchlein auf den linien mit Rechenpfenigen* (many editions from

1514) by Jacob Köbel (1460/65–1533), official surveyor of Oppenheim and manager of the municipal wine tavern, who also had his own printing press.[112] Köbel also printed his *Mit der Kryden oder Schreibfedern durch die Zeiferzal zu rechnen* (Oppenheim: J. Köbel, 1520) for calculating with Arabic numbers; the *Eyn new geordnet Vysirbuch* for calculating the capacity of barrels (Oppenheim: J. Köbel, 1515); and the *Geometrei* for formulas of land-surveying and the use of Jacob's staff (Frankfurt a. M.: C. Egenolff, 1535). In the course of the sixteenth century, university teachers began to appropriate the findings in the 'abacus' tradition. Michael Stifelius, for instance, used 'sum' to denote the unknown quantity in his *Deutsche Arithmetica* (Nuremberg: J. Petreius, 1545), and also edited Christoph Rudolff's *Die Coss* (Königsberg: A. Behm, 1553), which was a manual exclusively devoted to algebra. The Tübingen professor Johannes Scheubel (1494–1570) included a section on rules of algebra in his commentary on the first six books of Euclid's *Elements* in 1550 (Basle: J. Herwagen).[113]

Abacus texts were not so common in France. The first French work devoted to algebra of this period, Nicholas Chuquet's *Triparty en la science des nombres* (1484), remained unpublished until 1880, but a tract drawing on parts of it appeared in 1520 (Lyon: C. Fradin and G. Huyon), Estienne la Roche, *L'arismethique nouvellement composee*.[114] Jacques Peletier (1517–82) published his *Algèbre* (Lyon: J. de Tournes, 1554), which was in structure similar to Stifelius' manual and adopted several problems offered in Cardano's *Ars magna. De arte magna seu de occulta parte numerorum quae algebra et almucabala vulgo dicitur* (Paris: Beys, 1577) by Guillaume Gosselin (c. 1510–1604), which also drew upon Cardano's work, was more theoretical than Peletier's, possibly inspired by the publication of Diophantus' *Rerum Arithmeticarum Libri Sex* (Basle: E. Episcopius et Nicolai fr., 1575).[115] François Viéte (1540–1603) in his *In artem analyticem isagoge* 1591 (Tours: I. Mettayer) represented unknowns by upper-case vowels and knowns by consonants and sought to revive the ancient art of analysis.[116]

In England, writers of mathematical books drew upon continental works and aimed at practitioners who did not read Latin.[117] Robert Recorde's *The Grounde of artes* (London: R. Wolfe, 1543) was a handbook of commercial arithmetic aimed at technicians without university training, and his *The Whetstone of Witte* (London: J. Kyngstone, 1557) taught algebraic rules culled from the works of Cardano and Scheubel, and was the first English book to print '+' and '–' signs. Other useful books for mathematical practitioners included Leonard Digges' (1510–59) *A Boke named Tectonicon* (London: J. Day for T. Gemini, 1556), which was a manual on measurements; William Bourne's *A Treasure for Traveilers* (London: [T. Dawson] for T. Woodcocke, 1578), a manual for seamen, and Richard Benese's *Measurynge of All Maner of Lande* (Southwark 1537?) for landsurveying. The first printed Latin arithmetic, Cuthbert Tunstall's (1474–1559) *De arte supputandi* (London: in aed. R. Pynsoni,1522) drew on Pietro Borghi's *Nobel opera de arithmetica* (Venice: E. Ratdolt, 1484) and Luca Pacioli's *Summa de arithmetica.*

Astronomy, astrology, geography and cosmography

In the area of astronomy, Sacrobosco's *De sphaera* was the standard university textbook on planetary motion (based on Ptolemy, al-Battani and al-Faraghani) throughout the Middle Ages and the early modern period.[118] It was first printed in 1474 (Ferrara: A. Gallus) with the *Theorica planetarum* attributed to Gerard of Cremona, a short manual explaining paths of each planet.

Johannes of Gmunden (c. 1380–1442), who devoted his teaching at the University of Vienna to mathematics and astronomy, became noted for his lectures on astronomy, in which he sought to reform traditional teaching of planetary theories.[119] His student, Georg Puerbach (1423–61), continued this effort of reforming astronomy, informed by the humanistic movements inaugurated in Vienna by Aeneas Silvius Piccolomini (later Pius II).[120] Puerbach lectured on both Virgil's *Ennead* and on planetary theories at Vienna. In 1454, Johannes Regiomontanus (1436–76) heard Puerbach lecture on the reforms of Gerard of Cremona's *Theorica planetarum*. Regiomontanus also pursued a humanist reform of astronomy, which he advertised in a list of forthcoming publications when he set up a printing press at Nuremberg at the behest of King Mathias Corvinus of Hungary.[121] Regiomontanus printed the *editio princeps* of Manilius' *Astronomia* in 1473 after he had printed Puerbach's *Novae theoricae planetarum*, which was intended to replace Gerard of Cremona's *Theorica planetarum*.[122] In 1482, Puerbach's *Novae Theoricae* was added to an edition of Sacrobosco's *De sphaera* (Venice: E. Ratdolt). Some manuscript copies of Puerbach's *Novae theoricae planetarum* included volvelles, paper circles attached to a page with a piece of thread to allow rotating,[123] but it was not until the 1542 edition that they appeared in printed form. The 1515 edition (Paris: J. Petit and R. Chaudière) of Puerbach's *Theoricae novae planetarum* included woodcuts by Oronce Finé.[124]

There were 23 editions of Sacrobosco's *De Sphaera* printed before 1501.[125] The 1531 Wittenberg (J. Clug) edition of the *De sphaera* was the most frequently reprinted edition in the sixteenth century (23 times before 1601) and was the first printed octavo textbook of the *De sphaera*.[126] Its 1538 version of this textbook included three volvelles. The preface by Philip Melanchthon to this edition was often censored in Catholic countries.[127]

Sacrobosco's *De sphaera* was published in French in three different translations: by Nicholas Oresme (Paris, n.d.), by Martin Perer (Paris, 1546), and by Guillaume Desbordes (Paris, 1570). A German edition by C. Heynfogel appeared in 1516 (Nuremberg: I. Gutnecht). Italian translations began with Maurus Fiorentinus (Venice: B. Zanetti, 1537) and Francesco Pifferi (Siena, 1537), followed by A. Brucioli (Venice: F. Brucioli e i frategli, 1543); Dante de' Rinaldi's translation was edited by his grandson Egnazio Danti (1536–86) and published in 1572 (Florence: Giunti).

Another canonical textbook on astronomy was Ptolemy's *Almagest*, which appeared in print relatively late. Although Pope Nicholas V commissioned

George of Trebizond (1395–1484) to produce a Latin translation from the Greek in 1451, it was printed only in 1525 (Venice: L. Giunta) with corrections by Lucas Gauricus.[128] Cardinal Johannes Bessarion (1403–72), who did not approve of this version because it did not incorporate the criticisms of Theon of Alexandria, asked Puerbach in 1460 at Vienna to produce a new translation from the Greek. Puerbach unfortunately died in 1461, having finished only a Latin paraphrase of the first six books. The project was then taken over by Johannes Regiomontanus, whose Latin version was published as *Epytoma in Almagestum Ptolemaei*, posthumously in 1496 (Venice: J. Hamann). [see plate 1] A Latin text of the *Almagest*, based on Gerard of Cremona's translation from the Arabic, was printed in 1515 (Venice: P. Lichtenstein). A Greek text of the *Almagest* was edited by Symon Grynaeus and Joachim Camerarius in 1538 (*editio princeps*, Basle: J. Walder) from a manuscript given to Regiomontanus by Bessarion.[129] The Greek text of the first book only, with Erasmus Reinhold's scholia, was published in 1549 (Wittenberg: J. Lufft).

Ptolemy's astrological tract, the *Tetrabiblios*, meanwhile, had appeared in a Latin translation from the Arabic in 1484 (Venice: E. Ratdolt) with the *Centiloquium*, a collection of mainly astrological quotations from Ptolemy. The *Centiloquium* also appeared in a Latin translation by Giovanni Gioviano Pontanus, attached to his *De rebus coelestibus libri xiv* (Venice: in aed. Aldi et Andreae soc., 1519), a defence of astrology after the model of the *Tetrabiblos*.[130] The Greek text of the *Tetrabiblos* (*editio princeps*) was edited by Joachim Camerarius in 1535 (Nuremberg: J. Petreius) with Camerarius' Latin translation (books I, II, and parts of III and IV), and in 1553 a full Latin translation by Philip Melanchthon appeared with the Greek text (Basle: J. Oporinus). George of Trebizond's translation of the *Tetrabiblos* appeared in 1540 (Rome).

Ptolemy's *Geographia* first appeared in a Latin translation by Jacopo d'Angelo de Scarperia in 1475 (Vicenza: H. Liechtenstein) under the title *Cosmographia*, with no illustrations.[131] Its 1477 Bologna (D. de Lapis) edition included the first copper-engraving map to be printed in Italy.[132] A new Latin translation by Wilibald Pirckheimer using Regiomontanus' annotations was printed in 1525 (Strasburg: J. Grüninger).[133] The Greek text of the *De geographia libri octo* was printed (Basle: H. Froben & N. Episcopius) in 1533 (*editio princeps*). Erasmus's involvement in editing this Greek text has now been questioned, and it is likely that Sigismund Gelenius (c. 1498–1554), Froben's assistant, was responsible for editing the Greek text and even drafting Erasmus's preface.[134] A Latin translation from the Greek by Johannes Noviomagus appeared in 1540 (Cologne: J. Ruremundanus). In the same year 48 woodcut maps by Sebastian Münster were included in another edition of the *Geographia* from Basle (H. Petri). These maps were reused by the printer Petri in 1571 for an edition of Strabo's *Geographia*. The Italian translation of 1548 (Venice: N. Bascarini) by Pietro Andrea Mattioli (1501–77) was based on the Latin version of Pirckheimer corrected by Sebastian Münster.[135]

The appearance of maps, of course, was not confined to geography textbooks.[136] The first printed book to contain a map was Macrobius' commentary

on the dream of Scipio printed in 1483 (Brescia: B. de Boninis). The only fifteenth-century printed map to show any part of the Americas was Christopher Columbus' *Epistola de insulis super inventis* printed in 1492 (Basle: J. Wolff or M. Furter for J. Bergmann de Olpe).[137] Maps in printed books did not differ in this period from single-sheet maps in representing the New World alongside mythological creatures and peoples: in his *Cosmographia* (Basle: H. Petri, 1550), Sebastian Münster sought to make sense of the New World discoveries through classical mythology and history.[138] Accurate representations of the New World, with contemporary projections were often used, like earlier maps, as decorations in the sixteenth century to signify orders of the world or moral virtues. For instance, Egnazio Danti, together with Stefano Buonsignori, designed accurate world maps to decorate the new Guardaroba of Cosimo I at Palazzo Vecchio. The decoration of the Guardaroba, which was to be a cabinet of instruments and books, with an armillary sphere as the centrepiece, was to symbolize, as a whole, the created order of the universe.[139]

The term 'cosmographia' had gained wide currency in the fifteenth and sixteenth centuries, not only as another title for Ptolemy's *Geographia*, but also as a term for maps or charts with coordinates.[140] Thus, manuals accompanying terrestrial globes often bore that title, such as Martin Waltzemüller's *Cosmographiae introductio* (Strasburg: J. Grüninger, 1509) which was to accompany his small printed globe (gores of the world map were printed and pasted on a globe), and Johannes Schöner's *Luculentissima quaedam terrae totius descriptio* (Nuremberg: J. Stuchssen, 1515). Johannes Schöner (1477–1547) explained how to make a terrestrial globe in his *Cosmographia*.[141] Petrus Apianus (1495–1552), mapmaker, instrument maker, printer and writer, printed the *Cosmographicus liber* in 1524 (Landshut: J. Weyssenburger) which contained three pages of moving parts.[142] Cosmography, according to Apianus, was a description of the world (which included the four elements, the sun, moon and all the planets) by way of circles or spheres through which motions of the stars, variety of climate, days and nights were explained. Cosmography differed from geography in that the former approached the earth by spheres, while the latter focused on its surfacial configuration, such as mountains, oceans and rivers.[143] Apianus' *Cosmographicus* was corrected and an extra volvelle added in 1529 (Antwerp: in aed. R. Bollaert for J. Grapheus) by Reiner Gemma Frisius (1508–55), another very successful designer of instruments and globes.[144] In its 1533 edition (Antwerp: G. de Bonte for J. Grapheus) Gemma Frisius offered triangulation as a means of locating places. He also published the *De principiis astronomiae et cosmographiae* in 1530, which was to accompany the globe made by Frisius and Gaspar van der Heyden in 1529.[145] It went through 10 more editions until 1582. In its 1553 edition Gemma Frisius suggested the use of lapsed time in portable clocks to measure longitude.[146] Oronce Finé's *De mundi sphaera, sive Cosmographia, primave Astronomiae parte, libri V* (Paris: S. Colines, 1542), which taught elementary spherical astronomy, was used as textbook in northern European universities, including Pisa.[147] Robert Recorde

(1510–58) based his *Castle of Knowledge* (London: R. Wolfe, 1556) upon Finé's *De mundi sphaera*.[148]

Navigation and the magnet

This is also the period when, especially in England, solutions (actual and proposed) to navigational problems – such as finding longitude at sea using a magnetic compass – led to studies on Earth's magnetism. Many of the studies were carried out by mathematical practitioners, such as Robert Norman (fl. 1560–96), an instrument maker, who published on the dip of the magnetic needle in *The Newe Attractive, containing a short discourse of the magnes or lodestone* (London: J. Kyngston for R. Ballard, 1581); William Borough, whose *Discours of the variation of the compass* was to accompany Norman's work; William Barlow, who wrote *The navigator's supply* (London: G. Bishop, R. Newberry and R. Barker, 1597). Richard Eden (c.1508–76) wrote *A very necessarie and profitable Booke concerning Navigation* (London: R. Jugge, 1575), which was a translation of Jan Taisner's *Opusculum de natura magnetis et eius effectibus* (Cologne: J. Birckmann, 1562), which in turn was a plagiarism of the *Demonstratio proportionum motuum localium contra Aristotelem et omnes philosophos* (Venice: B. Caesanus 1554) by Giovanni Battista Benedetti, a student of Tartaglia's.[149] It is in the tradition of works by mathematical practitioners wishing to solve apparent and practical navigational problems, and extending their reasoning to natural philosophical theories of the Earth's magnetism, that William Gilbert's (1544–1603) *De Magnete* (London: P. Short, 1600) should be placed.[150]

Perspectiva and optics

For theoretical understanding of optical theory (including the physiology of the eye), medieval authors continued to be used: John Pecham's *perspectiva communis* (*editio princeps*, Milan: P. de Corneno, 1482) was frequently used as a textbook; and Witelo's *Opticae libri X* was used for more specialised and advanced study of optical theory. Petrus Apianus edited with Georg Tanstetter Witelo's *Optics* in 1535 (Nuremberg: J. Petreius). Pierre de la Ramée's followers also promoted optical studies. In 1557 (Paris: A. Wechel), the Greek text of Euclid's *Optics* (in reality Theon's *Opticae Recensiones*) was printed with a Latin translation by Jean Pena (1528–58), who had procured the Royal Professorship of mathematics at Paris with Ramée's patronage.[151] Pena's preface to this edition is notable for his attempt to raise the status of optics as a middle science. Friedrich Risner (d. 1580), who occupied the chair of mathematics established after the will of Ramée at the Collège Royal, edited and printed Alhazen's *De aspectibus* from manuscripts found by Ramée in the *Opticae*

thesaurus Alhazeni Arabis libri septem (*editio princeps*, Basle: N. Episcopius, 1572).[152] An Italian translation of Euclid's *Opticae* was made in 1573 by the Dominican, Egnazio Danti (1536–86), from Pena's edition. It is known that Giuseppe Moletti taught Euclid's *Opticae* in 1583/4.[153]

It should be noted that rudimentary principles of optics, including anatomical descriptions of the eye, were often found in manuals of linear perspective for artists. Piero della Francesca, for instance, who had a sufficient grasp of practical mathematics to compose a *Trattato d'abaco*, and had introduced some exacting mathematical techniques to his own painting, wrote the *De prospectiva pingendi* in which he demonstrated a grasp of Pecham's *perspectiva*. Leon Battista Alberti (1404–72) also used *perspectiva* theory to explain the rationale behind constructing linear perspective in the *De pictura*, which was not printed until 1540 (Basle: B. Westheimer). The *De artificiali perspectiva* (Toul: P. Jacobi, 1505) by Jean Pélerin Viator was the first printed book to offer a compendium of *perspectiva* theories for the construction of linear perspective. Pélerin's work gained wider currency when it was incorporated in the 1508 Strasburg edition of the *Margarita philosophica* by the Carthusian, Gregory Reisch. Daniel Barbaro incorporated Alhazen's theories in his *La pratica della perspectiva* (Venice: C. & R. Borgominieri, 1568). Egnatio Danti's edition of Giacomo Barozzi da Vignola's *Due Regole della Prospettiva Practica*, is notable for an assessment of theories of perspectives and of earlier and contemporary practitioners. Theories of linear perspective were further developed in Guido Ubaldo del Monte's *Perspectivae libri sex* (Pesaro: H. Concordia, 1600).[154]

It was not only the artists who drew fruitfully upon the mathematical and *perspectiva* tradition, however.[155] For instance, Albrecht Dürer's (1471–1528) instruction to use chords to map out three-dimensional space onto a screen in the *Underweysung der Messung* (Nuremberg: H. Andreae,1525) may have been a source for the formation of Kepler's theory of pinhole images.[156] Artists and woodcutters further played an important role in the printed 'scientific book': the sense of pride voiced by Ratdolt and Cavellat in their technical achievements in producing a book full of diagrams and charts, and the praise accorded to artists in the prefaces by authors (see for instance, Conrad Gesner in the *Historiae animalium* and Leonhard Fuchs in the *De historia stirpium*) confirm the importance of artists and woodcutters in producing illustrations.[157] Moreover, elaborately crafted title-pages began to carry messages about the nature and content of the book.[158] For instance, the title-page of Tartaglia's *Nova scientia inventa* (Venice: Stephano da Sabio, ad instantia di N. Tartaglia, 1537), a mathematical treatment of ballistics, depicts ballistics and Tartaglia on a par with other traditional liberal arts and authorities, thus confirming his attempt in the work to raise the status of ballistics.[159] One of the few authors who also cut their own illustrations was Oronce Finé, whose motto and title-page of the *Protomathesis* was copied by William Cunningham (1531–86) in *The Cosmographical Glasse* (London: J. Day, 1556).[160]

The supreme example of artist-cum-investigator of nature of this period, of course, is Leonardo da Vinci (1452–1519). While the extent to which his views

were formative for the technical and mathematical works of later generations is still unclear, recent scholarship has been successful in reassessing Leonardo's works in the light of earlier traditions. For instance, it is known that Leonardo had studied the anatomy of the eye and intended to compose an introduction to Pecham's *Perspectiva communis*.[161] The predominance of mechanical engineering drawings (most famously in the Madrid Codices I & II and Codex Atlanticus) within his oeuvre has been underlined and understood more recently in the context of his occupation as court engineer advising on military and engineering matters. Indeed, in this genre, Leonardo's drawings may be set in the Siennese tradition of mechanical and technical drawings which began at the beginning of the fifteenth century.[162]

Almanacs, ephemerides, calendars and tables

Perhaps the most important genre of publications from the financial point of view of the printers was the almanac. An astronomical calendar showing the position of planets in the zodiac (useful for casting horoscopes) for the year 1448 is known to have been one of the earliest printings by Gutenberg.[163] Roughly speaking, almanacs are tables of astronomical and astrological events of the coming year, such as positions and conjunctions of planets and stars, as well as phases of the moon and eclipses, and weather; an ephemerides provides similar information for several years running; calendars provide ecclesiastical information such as feast days, festivals and saints' days of the coming year; prognostications offer predictions derived from astrological and weather information as found in almanacs.[164] This is only a rough distinction, as many tracts combined elements of more than one of the above.

A systematic examination is yet to be undertaken for the printing of this genre, which is vast. An idea of the sheer bulk of the ephemerides literature may be gleaned through the listing by Houzeau/Lancaster,[165] while a sense of the variety of the format and content of *incunabula* calendars may readily be gained from the facsimiles of Heitz/Habler.[166] The library at the Royal Observatory of Edinburgh has a good collection of this genre.[167]

In 1474 Johannes Regiomontanus published his *Ephemerides*, which gave for the first time *daily* positions of sun, moon, Saturn, Jupiter, Mars, Venus and Mercury; the relative positions of planets; times of the new and full moons; feast days and Sundays for the years 1475 to 1506.[168] The printer's corrections were made to the text by hand, and contemporary users of Regiomontanus' *Ephemerides* frequently recorded weather observations in the wide margins, as did Christopher Columbus with Regiomontanus' *Ephemerides* for 1482 to 1488.[169] In 1499, Johannes Stöffler and Jakob Pflaum printed at Ulm its continuation for the years 1506 to 1532. The format of Regiomontanus' *Ephemerides* became standard for the next three centuries. In 1543, Oronce Finé published an ephemerides manual, *Les canons et documens très amples, touchant l'usage*

et practique des communs Almanachz quel'on nomme Éphémérides (Paris: S. de Colines, 1543),[170] which was translated by Humphrey Baker (fl. 1557–87) into *The rules and ryghte ample documentes, touchinge the Use of the common almanacks named ephemerides* (London: [T. Marshe], 1558). The weather section of Leonard Digges's (1510–58) *A prognostication of right good effect* (London: ?T. Gemini, 1555) was a translation of the corresponding part in the *Les canons*.[171]

Closely related to the almanac and ephemerides literature were various *tabulae*, which provided or assisted simple calculations of paths of planets and their relative positions. The Alfonsine tables (astronomical tables revised under the patronage of Alfonso X, el Sabio, 1221–84) provided figures for mean solar and lunar planetary orbits, declination of stars, relative positions of the sun and moon (opposition, ascension and conjunction) and lunar eclipses, and enabled the user to calculate planetary longitudes. This was used throughout the Middle Ages with the *Canon* of John of Saxony (first half of fourtheenth century).[172] The Alfonsine tables with John of Saxony's *Canon* was printed for the first time in 1483 (Venice: E. Ratdolt), while the *Canon* by Santritter were used for the 1492 edition.[173] Petreius, the Nuremberg printer, published improved Alfonsine tables, the *Tabulae Resolutae*, by Johannes Schöner in 1536 and another by Johann Virdung von Hassfurt in 1542. In 1552, Erasmus Reinhold published the *Prutenicae tabulae coelestium motuum* (Tübingen: U. Morhard), which incorporated the tables scattered in Copernicus' works and was intended as a guide for those who had been using the Alfonsine tables. The *Tabulae Bergenses* by Johannes Stadius (Cologne: A. Birckmann, 1566) and the *Ephemerides* of Michael Maestlin (Tübingen: G. Gruppenbach, 1580), Johannes Antonius Magini (Venice: 1580) and David Origanus (Frankfurt a. O.: Andreas Eichorn, 1599) were based on the *Prutenicae tabulae*, and acknowledged the mathematical skills of Copernicus, without mentioning his heliocentrism.[174] The improvement in predictive precision using Copernican tables were small.[175]

Regiomontanus also printed the *Calendarium* in 1474 in which he gave times of the full and new moons, solar and lunar paths, length of the day, feast days and Sundays for the years 1475 to 1531. It also included instructions for finding 'golden numbers' and movable feasts, constructing a sundial, and blood-letting. In addition, it contained paper instruments such as a lunar volvelle, horary quadrant and a sundial.[176] This was a popular calendar, and in 1476, Erhard Ratdolt, who may have worked at Regiomontanus' press in Nuremberg between 1474 and 1476,[177] printed another edition. The German edition, *Die deutsche Kalendar* was printed by Regiomontanus around 1474 and included newly coined words such as 'Sonnenuhr' for sundial and 'Finsternis' for eclipse.[178]

A major issue involved in the production of calendars was how to adjust a discrepancy, recognized since the Middle Ages, between the calendar year (which was essentially a lunar year) and the tropical (solar) year. The discrepancy meant that the vernal equinox was slipping behind the expected date of 21 March, as decreed at the Council of Nicaea (AD 325). The vernal equinox was

particularly important in the ecclesiastical calendar since the date of Easter (defined as the first Sunday after the first full moon after the vernal equinox) depended on it. Various methods of calculations and corrections had been suggested in the medieval *Computus* literature to align the calendar year and the tropical year, at least in some recurring cycle, so that a 'perpetual calendar' could be composed. The standard cycle was the nineteen-year one, and calendars usually gave the 'golden number' which indicated the position of the current year within the nineteen-year cycle. Final correction to the Julian calendar was agreed at the Council of Trent, and it was decreed in 1582 by Gregory XIII that years not divisible by four will not be leap years.[179]

Alongside ephemerides, almanacs and calendars were printed prognostication pamphlets which read into astronomical and natural anomalies contemporary and future disturbances. Popular prophetic pamphlets were printed actively during the years between 1478 and 1525 in Italy.[180] In Northern Europe, the prognostications of Johannes Lichtenberger became extremely popular.[181] Moreover, the 'great conjunction' of 1524 in which Saturn and Jupiter were to occupy the same region of the sky known as 'pisces', fuelled the printing of prognostication pamphlets, which predicted (or confirmed) political disturbances and natural disasters. This was the beginning of a printing vogue of pamphlets in which celestial portents such as comets, conjunctions, abnormal weather, as well as monstrous births, were linked to contemporary or imminent political and religious upheaval. This genre was exploited heavily by Lutheran reformers for their popular propaganda.[182] The range of natural portents used for such a purpose may readily be gleaned from the *Prodigiorum ac ostentorum chronicon* of Conradus Lycosthenes (Wolffhart) printed in 1557 (Basle: H. Petri). It is in this prognostic context that comets were observed and studied carefully.[183] Tycho Brahe wrote, for instance, a tract on the comet of 1577 which gave detailed astrological reading of the political and religious implications of his time.[184] Johannes Kepler also composed several calendars and prognostications from 1595 onwards.[185]

Instrument books

The new technology of printing also had an important bearing on the diffusion of paper instruments, such as volvelles or cut-out quadrants.[186] The state of the representation of instruments in books varied from purely heuristic ones to those which were accurate and intended to be used after cutting them out and pasting them on wooden frames. Gregory Reisch's *Margarita philosophica*, for instance, contained pictures of instruments such as the Jacob's staff, quadrants and armillary spheres, which were more heuristic than practical.[187] Oronce Finé's *In Proprium planetarum aequatorium* (Paris: H. Gourmont, 1538), in contrast, contained an equatorium which could be used for accurate calculations. Petrus Apianus' *Astronomicum Caesarium*, printed by himself, was a lavishly

coloured edition with 37 full-page volvelles intended for the Emperor Charles V, his brother and a few others. Apian's *Instrument Buch* (Ingolstadt: P. Apian, 1533) contained moving parts as well as paper instruments to be cut out. His luxurious as well as more affordable books with volvelles and other movable parts popularized this genre of book which served as an 'instrument', but Francesco Maurolico (1494–1575) objected to the coloured volvelles as they were more ostentatious than useful.[188]

There were also several manuals which explained how to construct and use an instrument. Johannes Angelus' *Astrolabium planum* (Augsburg: E. Ratdolt, 1488) was the first printed book to contain the word astrolabe in the title, and it was predominantly a manual for casting horoscopes.[189] Regiomontanus' treatise on the construction and use of armillary sphere, the *Scripta de torqueto, astrolabio armillari et observationibus cometarum*, was edited by Johannes Schöner in 1544 (Nuremberg: I. Montanus & V. Neuber). The *Elucidatio fabricae ususque astrolabii* (Oppenheim: J. Köbel, 1512/13–) by Johannes Stöffler (1452–1531) was a didactic tract including paper astrolabes designed to be cut out and pasted on wood. Other sixteenth-century books on the construction and use of the astrolabe were: Jacob Köbel's *Astrolabii declaratio* (Mainz: P. Jordan); and Johan Martin Poblacion's *De usu astrolabii compendium* (Paris: R. Estienne, 1518); its German translation by Johannes Copp, town physician to St Joachimstahl, the *Wie man diss hochberumpt astronomischer und geometrischer Kunst Instrument Astrolabium brauchen soll* (Bamberg: G. Erlinger for C. Weidlins, 1525); and further an English translation by Robert Tanner, *A Mirror for Mathematiques...contayning also an order howe to make an Astronomical instrument, called the Astrolab, with the use thereof* (London: B. Charlewood, 1587), which was the first printed account of a standard astrolabe in English. The first work in French on the astrolabe was Dominque Jacquinot's *L'usaige de l'astrolabe, avec un traicté de la Sphere* in 1545 (Paris: I. Barbe, sold by I. Gazeau et V. Sertenas). Egnatio Danti (1536–86), who advised Cosimo I de' Medici on his collection of maps and instruments, and also built an astronomical quadrant and equinoctial armillary on the facade of Santa Maria Novella in Florence,[190] published the *Trattato dell'uso et della fabbrica dell'astrolabio* in 1569 (Florence: J. Giunti).

The first separately printed work on sundials was Petrus Apianus' *Ein künstlich Instrument oder Sonnen Ur* (Landshut: J. Weyssenburger) in 1524.[191] Sebastian Münster published the *Erklerung des newen Instruments der Sunnen* (Oppenheim: J. Köbel, 1528), which included five volvelles. His systematic study of sundials was translated into Latin in 1531, *Compositio horologiorum* (Basle: H. Petri). Jacob Köbel too printed a tract on sundials, *Eyn künstliche Sonn-Uhr* (1532). Thomas Fale's *Horologiographia* (London: T. Orwin, 1593) was the first book printed in England which was devoted exclusively to sundials.

Petrus Apianus' also printed the *Quadrans astronomicus* (Inglostadt: P. Apian 1532), which contained instructions on how to make a paper quadrant. Johannes Dryander added a section on a quadrant to Köbel's *Geometrei*, and later translated it into Latin. In his *Astronomicae instauratae mechanicae* (Wandsbeck:

Heinrich von Rantzau, 1598), Tycho Brahe (1546–1601) offered a picture and an account of his great mural quadrant, among descriptions of other instruments and his castle 'Uranibourg' on the Island of Hven.[192] Like Regiomontanus, Apianus Köbel and others, Brahe was another figure who wrote on astronomy and cosmology, made instruments and owned his own printing press. Compared to Regiomontanus' sense of mission to promote the humanistic reform of astronomy, or Apianus' popularization of paper instruments, however, Tycho's publication seems to have been aimed at a narrower and more specific class of readers – at the educated nobility with an interest in astronomy rather than at the general book-reading market. Thus, many extant copies of the *Astronomicae instauratae mechanicae* have been established as presentation copies to dignitaries such as Ferdinand de' Medici, Duke Ulrich of Mecklenberg, Duke Friedrich Wilhelm of Saxony, and the Venetian Republic, and many of them are lavishly coloured and bound in silk.[193]

Johannes Schöner wrote the *Opusculum geographicum ex diversorum libris ac cartis summa cura et diligentia collectum* (Nuremberg: J. Petreius, 1533) and the *Globi stelliferi, sive sphaerae stellarum fixarum usus* (Nuremberg: J. Petreius,1533), handbooks for the terrestrial and celestial globes respectively, both of which were dedicated to John Frederick of Saxony, for whom Schöner had made a pair of terrestrial and celestial globes. The *De orbis situ ac descriptione*, a handbook accompanying a terrestrial globe (Antwerp: M. Keyser for R. Bollard, ?1527) by the Franciscan monk Franciscus, was unusual in that it had an imperial privilege for five years not only for the text, but also for the globe accompanying it.[194]

It is perhaps not surprising therefore that instruments begin to appear in collections of books and manuscripts. One of the most famous collections at the end of the fifteenth century – Regiomontanus's – was known for its collection of books, manuscripts (many copied on his travels in Italy and from Cardinal Bessarion's library) as well as instruments possibly made by himself. The collection was sought on his death by Maximilian I, Frederick the Wise, King Mathias Corvinus and many others, none of whom succeeded in acquiring the collection as a whole, because of its high price set by the executors. The collection was gradually dispersed. Some of the manuscripts were made use of in print by Johannes Schöner, Joachim Camerarius and Willibald Pirckheimer, while many others, such as his copy of Euclid's *Elements*, once owned by Albrecht Dürer, are lost.[195] Recently, however, it has come to light that an astrolabe presented to Cardinal Bessarion by Regiomontanus may have survived.[196] Instruments became a standard part of sixteenth-century libraries of people with interest in mathematics, astronomy, astrology and medicine. John Dee's (1527–1608) famous library contained a quadrant, compasses, clocks, a pair of Mercator's celestial and terrestrial globes and a lodestone.[197] Other collections including instruments are that of Andrew Perne (d. 1589), Master of Peterhouse Cambridge, which contained, among over 2500 books, several astrolabes, quadrants, a theodolite, a Jacob's staff, clocks and compasses.[198]

Nicolaus Copernicus (1473–1543)

The last fifteen years have seen tremendous advance in the bibliographic study of Nicolaus Copernicus' *De revolutionibus* spearheaded by Owen Gingerich. The Wittenberg professor Georg Joachim Rheticus visited Copernicus in 1539 and encouraged him to print his works.[199] Rheticus published the *Narratio prima* in 1540 (Gdansk) and, following its favourable reception, persuaded Copernicus to publish his tract on the revolutions of the heavens.[200] The Nuremberg printer Petreius asked Rheticus to secure the printing of the latter work on his behalf,[201] and copies of his publication were offered by Rheticus to Copernicus as gifts.[202] Rheticus began supervising the publication of the *De revolutionibus* in Nuremberg with Petreius in 1542, but did not see to the end of its publication. The final product contained an anonymous letter to the reader, quickly identified as written by Andreas Osiander, and two additional words to the title, *coelestium orbium*. Rheticus had not intended these insertions and they were duly crossed out in his copies.[203] Indeed, it has been shown that the prefaces of Osiander and of Copernicus show different concerns and values: Osiander, a Lutheran pastor, beseeches the reader for a fair hearing of what seems like a disciplinary confusion in the context of scholarly learning; Copernicus, a clerical humanist, sought astronomical reform by appealing to the aesthetics of symmetry and decorum prevalent in the ecclesiastic court of Paul III.[204] Some copies of the first edition include the printer's *errata* list up to folio 146 (some with a title page print on the reverse), but uniform corrections by contemporary hands beyond folio 146 suggest the existence of a more extensive list of *errata* shared by a group of astronomers.[205] Contemporary annotations in surviving copies have proven significant for historians of science: for instance, copies with identical annotations shed new light on the hitherto unappreciated role of itinerant mathematical tutors such as Jofrancus Offusius and Paulus Wittich in disseminating interpretations of Copernicus.[206]

A world census carried out by Gingerich of the two sixteenth-century editions (Nuremberg: J. Petreius, 1543; Basle: H. Petri, 1566) will no doubt provide us with a more definitive picture; currently 250 copies of the first edition and 290 copies of the second have been located. It seems that the original print run was around 400 to 500 copies for each edition, the first edition probably staying in print for about 20 years. There is no evidence that copies of the first edition were originally distributed in England through English booksellers, while copies of the second edition were readily found in England, Italy and France.[207] [see plate 2]. The *De revolutionibus* was placed on the *Index of Prohibited Books* in 1616, and requisite corrections were spelt out in 1620.[208] It seems that 60 per cent of the copies in Italy (and hardly any in Spain[209] or Portugal) were censored. The *De revolutionibus* was taken off the *Index* in 1758.

Study of animals, birds, fish and minerals

While scholarly study of animals tended to centre on their medicinal uses, as found in Dioscorides' *materia medica* or in Pliny the Elder's *Historia naturalis*, there were also plenty of other sources such as Aesop's *Fables* or the medieval *Physiologia* for animal habits and animal lore.[210] Conrad Gesner sought to collect, with the help of his friends, all such information known of all creatures in his monumental five-volume *Historiae animalium* (Zurich: C. Froschauer, 1551–58).[211] It included descriptions of quadrupeds, birds, fish, shellfish, insects and reptiles, accompanied by illustrations drawn from life or copied from other sources, including the picture of the rhinoceros by Albrecht Dürer. These illustrations were intended to be coloured at extra cost at the printer's from a master copy.[212] The pictures were separately reissued as the *Icones animalium* (Zurich: C. Froschauer, 1553), though Gesner made a blunder by dedicating it to Elizabeth I without her permission and had to apologize to her through the mediation of his friend, the physician John Caius.[213] The *Historiae animalium*, which included medicinal uses of each animal, also exhibited Gesner's philological interest: names of each animal in different languages, etymology of their names, their medical or geographical equivalents; their uses in metaphors; and proverbs and maxims associated with the animals. Such a compilation of all possible meanings attached to an animal typified a vogue of 'emblematic' approaches to nature.[214] The general scheme of classification of animals itself, however, remained Aristotelian (largely following Aristotle's *De animalibus*), throughout the sixteenth century.

For his *Historia animalium*, Gesner drew upon works of others who had more specialized interests, such as Pierre Belon (1517–64), who had composed the *Histoire naturelle des estranges poissons marins* (1551), a collection of fish, which also included dolphins and the hippopotamus.[215] Belon also wrote the *L'histoire de la nature des oyseaux* (1555), which was a study of birds based on Aristotelian classification,[216] while earlier works on birds tended to focus on falconry.[217] Guillaume Rondelet (1507–66) also published a book on fish, the *Libri de piscibus marinis* (Lyon: H. Bonhomme, 1554/55) which sought to include all aquatic animals, including marine mammals, beavers and sea-monsters. A French translation (possibly by his student Laurent Joubert) appeared in 1558, *L'histoire entière des poissons*.[218]

The scholarly study of minerals also belonged to the study of the *materia medica*. Eucharius Rösslin's *Kreuterbuch*, for instance, included extensive discussion on the medicinal virtues of gems and minerals.[219] Following the expansion of the mining industry, especially in Germany and Italy, however, a new kind of literature appeared:[220] the *Bergbüchlein* by Calbus of Freiburg (d. 1523), a dialogue on the profitability of mining, was aimed at prospective investors; Vannoccio Biringuccio (1480–1538), supervisor of iron factories developed by Pandolfo Petrucci in the Boccheggiano valley, wrote the *De la Pirotechnia* in 1540 for noble patrons and well-born prospective investors who were not

familiar with mining;[221] and Lazarus Ercker (d. 1593) who made recommendations on Bohemian mines to the Emperor Rudolf II, wrote a practical guide on assaying for beginners, the *Beschreibung der allervornehmsten mineralischen Erze und Bergserksarten* (Prague: G. Schwartz, 1574).[222]

The study of minerals was promoted extensively in Latin by Georg Agricola (1494–1555), humanist-physican and apothecary at St Joachimsthal, an important mining centre. He published in 1530 (Basle: in off. Frobeniana) the *Bermannus*, a dialogue on recovering the classical knowledge and use of minerals as medicaments, with a glossary of Latin mineral terms with German equivalents.[223] Agricola later became mayor of Chemnitz, but returned to St Joachimstahl to finish a larger work on minerals over which he had toiled for 20 years, the *De re metallica* (Basle: H. Froben and N. Episcopius, 1556), which was a defence of mining after the model of Columella's defence of farming. It contained 292 illustrations that took Blasius Wetting (also of St Joachimstahl) three years to finish.[224] The Froben Press at Basle had the monopoly on Agricola's writings: they issued the only sixteenth-century German translation by Philip Bechius in 1557 and the only Italian translation by Michaelangelo Florio in 1563.

Alchemy, distillation, magic and the secrets of nature

These works on mining and the study of minerals and metals naturally contained alchemical ideas for manipulating metallic reaction for various uses: the term 'chymia' (meaning alchemical processes), for instance, began to appear prominently in the works of mining of this period, such as in Agricola's *Bermannus* and the *De re metallica.* The term also gained further currency through Conrad Gesner's *De remediis secretis* (Zurich: A. Gesner, 1552), a distillation manual of herbal and mineral medicine.[225] Distillation manuals were particularly useful for those seeking to use alchemical processes for medicine: Paracelsus (c. 1493–1541), for instance, sought to cure 'external' causes of diseases (caused by the mineral world and atmosphere) with medicine derived from metals and minerals, and drew heavily on this genre of knowledge in the *Archidoxa* (Munich: A. Berg 1570).[226] The best-known distillation manual of this period was Hieronymus Braunschweig's *Das Buch der Kunst zü distilieren* (Strasburg: J. Grüninger 1500), which went through many editions and was translated into English and printed by Lawrence Andrewe (fl. 1510–35) in *The vertuose Booke of distyllacyon* (1527 onwards). Conrad Gesner's pseudonymous dictionary of distillation terminology, the *Thesaurus Eunonymi Philiatri* (Zurich: C. Froschauer 1552), was translated by Peter Morwyng (1530–73) and printed by John Day as *Treasure of Eunonymus* (1559 onwards), with illustrations. Books with alchemical content thus ranged from mining manuals, distillation handbooks, medical guidebooks to recipes for transmuting base metal into gold.[227]

Magic – a knowledge and practice which (it was believed) provided the knower with the power to cause wondrous effects by manipulation of objects and signs – similarly drew upon a variety of sources, such as university natural philosophy or mathematics: Pythagorean belief in the special meaning of mathematical ideas contributed to numerology; astrological theories were the foundation of 'sympathetic' magic in which, for instance, engraving the figure of Venus on a gem in a ring was believed to be effective in attracting the power of the planet Venus; and medical theories of spirits provided the basis for using music in order to maintain health of the human soul.[228] It is important to note that this is a period when the distinction between magic and non-magic; illicit and licit knowledge; the occult and the manifest, varied tremendously and were frequently blurred.[229]

As Scribner has pointed out recently, the distinction between magical and non-magical/scientific as mutually exclusive categories and a view of the Reformation as a catalyst for the latter triumphing over the former, are post-Enlightenment categories which do not do justice to the works and practices of this period.[230] The importance of the alchemical and magical tradition of this period, particularly for seventeenth-century figures such as Leibniz and Newton, has been well recognized by historians of science.[231] Instead of using the dichotomous scheme of 'science' vs 'pseudo-science', recent scholars have focused on unravelling the particular set of values and social customs of the princely court (as different from the institutional setting of the university) which supported and practised different kinds of studies of nature, namely alchemy, magic and 'secrets' of nature. Alchemy appealed to many rulers and princes, such as the Medici dukes and Habsburg Emperors, not only for its claim to transmute metals (and its implication of financial gain), but also as esoteric knowledge divinely endowed for princely rule.[232] Magic also appealed to many princes as a secret source of power: the *Magiae naturalis libri xx* (1589) of Giambattista della Porta (1535–1615), for instance, was a prime example of a collection of secret recipes and gadgets offered as esoteric knowledge to the ruling elite and those who could pay.[233] Such knowledge and practice differed in form, content and function from the pursuits of knowledge within university walls, as is manifest from the kinds of books that were produced. Claims to secrecy often clashed with the public nature of the printed book: many books of secrets were to be found in manuscripts or in ciphers. The manuscript book thus acquired a renewed rôle as an alternative, restricted medium, compared to the printed book, for 'secrets'.

As it is misleading to consider this period as a time when early forms of 'science' were rooting out 'magic' and 'superstition', so it is equally misguided to presume that the printed book prevailed over the manuscript book as the means to acquire knowledge about nature. The size, format, content and price of books in this period varied as widely as the range of practices, expectations and uses of knowledge about mathematics, nature and the cosmos.

Notes

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3. It should be noted that the *Index Aureliensis* does not provide a comprehensive listing of locations, and that therefore it cannot be used for compiling a world census of a given title. There are, however, several extremely useful, separate publications based on the *Index Aureliensis*, such as F. Edward Cranz (1984), *A Bibliography of Aristotle Editions 1501–1600*, with addenda and revisions by C.B. Schmitt, Baden-Baden: Valentin Koerner, 2nd edn; Muller, J. and Róth, E. (1967), *Ausereuropäische Druckereien im 16. Jahrhundert: Bibliographie der Drucke*, Baden-Baden: Heitz; and *Index Aureliensis Catalogus librorum sedecimo saeculo Impressorum*, Tertia pars tomus 1, Nieuwkoop: de Graaf.
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38. Schmitt, C.B., *Aristotle and the Renaissance*, (note 34), p. 14.
39. I follow here the introductory remarks in Cranz, *A Bibliography of Aristotle Editions 1501–1600* (note 3) pp. XI–XIV, and in Lohr, *Latin Aristotle Commentaries II* (note 20), pp. xiii–xv. These two works are standard references for Aristotelian imprints of this period. A list of Aristotelian imprints up to 1600 including incunables by Charles H. Lohr is forthcoming in the *Catalogus Translationum et Commentariorum*. For the pitfalls associated with studying the reception of Aristotelian philosophy through incunable editions, however, see Jill Kraye (1995), 'The printing history of Aristotle in the fifteenth century: a bibliographical approach to Renaissance philosophy', *Renaissance Studies*, 9(2), 188–211.
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Chapter Five

Words of Nature: Scientific Books in the Seventeenth Century

Tara Nummedal and Paula Findlen

In the course of the seventeenth century the printed word became an increasingly important tool for natural philosophers. They discussed it self-consciously, used it voraciously, and clamoured to include the latest technological improvement in their books. Writing in 1600, the German astronomer Johannes Kepler (1571–1630) linked publication to the growing publicity of knowledge. In his history of astronomy he presented ancient astronomy as a largely private enterprise characterized by poor communication among its participants, who often had little knowledge of each other's activities. Nor, Kepler remarked, did that knowledge survive much beyond their lifetime since books did not yet have a central role in the transmission of ideas, 'owing to the lack of printing, I imagine'.[1] Printing, in short, was not simply a technology in the eyes of this early modern natural philosopher. It was a medium that transformed the very definition and content of knowledge itself, giving books a status in the learned world that they could not have enjoyed in a society that valued the oral transmission of ideas.

When Francis Bacon (1561–1626) wrote in 1620 that printing had changed 'the whole face and state of things throughout the world', he had only scanty evidence of how printing would affect the study of nature.[2] Prior to the seventeenth century printing had become an important medium for physicians, astronomers, naturalists and encyclopaedists to present their ideas, but few had the means and the patronage to publish regularly. Even wealthy nobles such as the Danish astronomer Tycho Brahe (1546–1601) resolved the problems of publishing by self-publishing, financing their own printing presses in order to control better the transformation of their ideas into books.[3]

3. Hevelius, *Selenographia* (1647).
Reproduced courtesy of Bernard Quaritch Ltd.

More typical was the case of the Italian naturalist Ulisse Aldrovandi (1522–1605), who exerted great effort to publish four volumes of his natural history before his death, leaving hundreds of unpublished manuscripts to gather dust. Like Bacon, Aldrovandi greatly admired the capacity of print to transform knowledge. 'And it's incredible but true', he recorded in one of his notebooks, 'that one man alone can print more in one day than even the quickest writer could scribble in two years'.[4] Printing was the means of accelerating the process of creating the new encyclopaedia of knowledge, making transitory words seemingly immortal through their technological transformation. Aldrovandi devoted most of his efforts at the end of the sixteenth century to seeing his ideas into print. As impressive as the appearance of his three-volume *Ornithologiae* (1599–1603) is, we need to remind ourselves that it was the product of some forty years of sustained efforts to attract multiple patrons willing to finance an illustrated natural history. In 1601, when he was almost eighty years old, Aldrovandi was still hoping that the pope might grant him a stipend to print his works.[5] This is surely one of the many reasons that Aldrovandi had the engravers of his *Ornithologiae* insert a portrait of himself presenting his book to the pope [see plate 4]. The production of a book was no small accomplishment at the end of the Renaissance, a Herculean labour even greater perhaps than the revision of Aristotle's ancient encyclopaedia of knowledge.

As it turned out, it was far easier to produce words than to print them. Even as late as the eighteenth century, scholars recalled with amazement Aldrovandi's efforts to transform manuscripts into books.[6] Having watched a number of friends, such as the Swiss naturalist Conrad Gesner and the papal physician Michele Mercati, die without providing for the posthumous publication of their works, Aldrovandi was not about to recede into obscurity.[7] In 1603 he secured an agreement from the Senate of Bologna, who accepted the gift of his museum of natural history in exchange for agreeing to publish the remainder of his natural histories. By 1667, eight more of Aldrovandi's books had rolled off the presses, edited by the custodian of the *Studio Aldrovandi* and financed by the city.[8] Perhaps feeling that they had more than met the terms of the agreement and that no family members would harass them for not fulfilling the stipulations of the will, the Senate ceased to publish. Visitors to the museum continued to wonder at the quantity of writings stuffed in sacks and placed in a room of the museum. But no more were printed. An additional curiosity of the tour of Aldrovandi's museum suggested why: therein lay hundreds of unsold natural histories, beautiful to look at indeed but with precious few readers.

In acknowledgment of this surplus of natural histories, in 1647 the Senate of Bologna sold 930 volumes of Aldrovandi's writings. While the general public may have been uninterested, scholarly book collectors who read such works as Gabriel Naudé's *Advis pour dresser une Bibliothèque* (1627), which recommended acquiring Aldrovandi's works to fill out one's library in natural history, salivated at the prospect of obtaining a specimen from this famous project. One such copy made its way to England where it was bought by the English natural

philosopher and curator of experiments for the Royal Society, Robert Hooke (1635–1705), in a public auction in 1689. Hooke paid £8.15s for a single volume, one of the highest prices he ever recorded for a book.[9] Within a century, Aldrovandi's books had become collector's items, valued by a reading public which increasingly saw the ownership of books as an important part of investing in culture.

Aldrovandi's ability to enlist a city in the posthumous publication of his work was an unusual agreement, to say the least. Ten years later, the Neapolitan magus Giovan Battista della Porta (1535–1615) had his fellow members of the Accademia de' Lincei promising to collect his many works into a grand *Opera Omnia* but this also occurred in response to the perceived value of della Porta's library, scientific collections and antiquities to the activities of the academy.[10] Few natural philosophers owned something so valuable that they could barter it for the cost of printing their ideas. Even Isaac Newton (1642–1727) would not have seen the *Principia* (1687) into print without the generous financing and editing of Edmund Halley (1656–1741); only after the success of the first edition did the learned and publishing community consider it truly worth printing.[11] The realities of publishing beleaguered more than one natural philosopher who discovered, to their chagrin, that the secrets of nature, unless they promised great novelties or good health, rarely interested much of the reading public. As Henry Oldenburg, secretary of the Royal Society of London, confessed to the Dutch mathematician Christiaan Huygens in 1669: 'Our booksellers are very lazy and careless in the business of selling scientific books because of the small number of those who take pleasure in these compared with other sorts of books.'[12]

Scholars who wished to publish were often bound to the rules of the marketplace. Publishing was an investment, and investors needed to assure themselves that the product was worthy of their financing before sending a book to press. As a result, the responsibility for 'selling science' devolved as much to the author as the publisher. Philosophers needed to persuade their patrons and readers that natural knowledge deserved the same place as history, law, theology and poetry in the libraries of the educated elite. For these reasons, the decision to publish was rarely at the discretion of an individual; instead it was a collective decision made by a community that considered the pursuit of science a worthy though rarely profitable undertaking.

As Elizabeth Eisenstein noted in her influential *The Printing Press as an Agent of Change* (1979), the topic of printing occupied the thoughts and shaped the aspirations of many early modern intellectuals.[13] It emerged not just as a private fantasy expressed in scholarly marginalia but also in public discussions of the new shape of knowledge. Scholars discussed their desire to be published and their frustrations in attaining that goal, and evaluated the best strategies for disseminating their ideas to the various reading publics. Searching for the best means to communicate knowledge, natural philosophers invented new genres of scientific writing and furthered the debate about the role of illustrations that

had begun in the sixteenth century. They also focused on the process of acquiring books, through private sales, public auctions, gift-giving and the creation of library catalogues, presenting themselves as sophisticated consumers of this artefact. Such discussions redefined their relationship to the printed word and ultimately influenced the nature and appearance of early modern scientific publications.

The author as printer

When at the beginning of the seventeenth century Johannes Kepler reflected on the effects of the printing press on European cultural and intellectual life, he joined a growing consensus in the republic of letters which expressed awe at the profound changes the press had stimulated. Like Bacon, he believed that the press was far more than a more efficient way to disseminate information. In his *De Stella Nova* (1606), Kepler remarked:

> After the birth of printing books became widespread. Hence everyone throughout Europe devoted himself to the study of literature. Hence many universities came into existence, and at once many learned men appeared so that the authority of those who clung to barbarism declined ... From the universities and [their] license to hold disputations, from the abundance of books and from the convenience of printing, as well doubtless as from learning and public unrest, there has in the end sprung that immense and forever memorable secession of very many regions of Europe from the see of Rome ... What shall I say of today's mechanical arts countless in number and incomprehensible in subtlety? Do we not today bring to light by the art of printing every one of the extant ancient authors? Does not Cicero himself learn again how to speak Latin from our many critics? Every year ... the number of writings published in each field is greater than all those produced in the past thousand years. Through them there has today been created a new theology and a new jurisprudence; the Paracelsians have created medicine anew and the Copernicans have created astronomy anew. I really believe that at last the world is alive, indeed seething ... [14]

Foreshadowing Bacon's comments fourteen years later (as well as those of several historians in the late twentieth century),[15] Kepler believed quite strongly that the proliferation of books during the sixteenth century had brought about revolutionary changes both in learned circles and in society more generally.

The press had an equally profound effect on Kepler's own life as a producer and consumer of knowledge. He was immersed in print culture from his early days as a student at the University of Tübingen, where his humanist education gave him an appreciation for close and critical reading of texts.[16] These reading skills continued to be important throughout his life since, like many natural philosophers, Kepler still looked to ancient and modern books for much of his information about the natural world. But his reading was not limited to natural philosophy; he also read broadly to be conversant in the learned culture of his patrons, fellow courtiers and humanists. Thus, like his more politically minded colleagues, Kepler too read and commented on the most fashionable author at

the German courts, Tacitus. Reading and producing texts, increasingly in printed form, lay at the heart of seventeenth-century intellectual and elite social life.[17]

When Kepler began to write his own books, he quickly became as involved in the production of books as he was in their consumption. His correspondence reveals a man who seems to have spent as much time, energy and money trying to print his work as he did on astronomy itself. Writing and printing were for him two complementary halves of the production of knowledge, as he indicated in the frontispiece he designed for his *Tabulae Rudolphinae* (1627) [see plate 5]. At the bottom of the temple in the engraving, two panels appear on either side of the central image of the Isle of Hven. On the left, Kepler sits at a table busily calculating and designing the temple of astronomy above him; on the right, a printer and his assistant labour at the press, transforming Kepler's work into the shape of a book. By giving the two images equal status in the frontispiece, Kepler suggests that both the astronomer and the printer, the producer of ideas and the producer of books, have an equally important place in the work of astronomy.

Kepler began his career as a creator of books with the publication of the *Mysterium Cosmographicum* in 1597. Here he discovered for the first time what was to remain his biggest problem throughout his life: financing publication. The reality of the marketplace made it difficult to persuade printers to take on the costs and the risks of publication themselves. In 1609, for example, the Leipzig schoolmaster Sethus Calvisius wrote to Kepler that he had tried to enlist a printer for one of Kepler's treatises on comets, but that, unfortunately, the printer had refused, 'because comets have almost vanished from the minds of men and no hope remains of selling these copies'.[18] In publishing the *Mysterium Cosmographicum*, Kepler ran into a similarly reluctant printer. He had to agree to purchase 200 copies of the book from the printer as a way of absorbing some of the risk.[19]

One might expect that Kepler would have tried to sell these copies of the *Mysterium Cosmographicum* to recoup his initial investment. He chose instead, however, to give away several dedicated copies of the book to the Estates of Stiermark in hope of receiving a small sum of money or perhaps even future patronage in exchange. Unfortunately, he was disappointed (the Estates did not return Kepler's gesture until three years later, when they granted him 250 *gulden* – just enough money for him to flee religious persecution in Graz).[20] But Kepler's willingness to give away copies of the book indicates that he saw the book's value not necessarily as monetary, but as an important tool in obtaining patronage and positions.

Kepler continued to use his books throughout his life to reward generous patrons, and to entice potential ones. He even wrote an entire essay, *Strena, seu De Nive Sexangula* (1611) as a New Year's gift for one of Rudolf II's councillors, Johann Matthäus von Wackenfels (1550–1619). Kepler published the gift a year later as a way to publicly reward this powerful broker in his chain of patronage to the Holy Roman Emperor. While Kepler rewarded generous men

such as Wackenfels, he expressed his dissatisfaction with unresponsive patrons by leaving them out of his next dedication. In 1627, for example, the Tübingen professor Wilhelm Schickard suggested that Kepler dedicate a few copies of the *Tabulae Rudolphinae* to the Senate of the University of Tübingen. Kepler dismissed the idea, explaining that such a gesture was not worth the effort since when he dedicated several copies of his *Astronomia nova* to the Senate in 1609, he received nothing from them.[21]

Kepler also sent gift copies of the *Mysterium Cosmographicum* to prominent natural philosophers, hoping to use the book to further his scholarly reputation. Fortunately, he was more successful in this arena than with prospective patrons. The Italian mathematician Galileo Galilei (1564–1642), for example, responded with pleasure at having found another Copernican, 'an associate in the study of the Truth who is a friend of the Truth'.[22] Tycho Brahe was even more impressed. He invited Kepler to visit him in Prague and introduced him into the court of the Holy Roman Emperor Rudolf II. This relationship, initiated with a book, eventually led Kepler to succeed Brahe as Imperial Mathematician upon the Dane's death in 1601. Thus, although publishing books cost Kepler money in the short run, and did not always turn out to be particularly valuable ploys for patronage, they did help launch his career. Kepler must have felt that, in the long run, the books certainly paid for themselves.

Thirty years (and several books) later, Kepler was already well established among scholars and his contributions to natural philosophy and astronomy were recognized; and yet he seemed even more determined than before to bring his works into print. Indeed, the last years of Kepler's life seem to be dominated by an almost frantic attempt to publish his remaining manuscripts – no small task in the midst of the Thirty Years' War which was decimating central Europe. The most anticipated of these works was Kepler's mammoth *Tabulae Rudolphinae*, a collection of astronomical tables formulated out of Brahe's meticulous observations. After decades of receiving letters from all over Europe asking when the valuable data would be available, Kepler finally told the English astronomer Edmund Gunther in 1623, 'I can see the harbour'. A few months later he discussed the completion of this work more dramatically to his friend and correspondent in Strasbourg, Martin Bernegger: 'The Rudolfine Tables, sired by Tycho Brahe, I have carried in me for twenty-two years, as the seed is gradually developed in the mother's womb. Now I am tortured by the labours of birth.'[23]

The 'labours of birth' were indeed painful, and Kepler devoted the next few years of his life and substantial monetary resources to printing the *Tabulae*.[24] Since the book was named after Tycho and Kepler's original patron, Emperor Rudolf II, Kepler expected money from the imperial coffers to print it. Emperor Ferdinand II owed Kepler large amounts of back-salary and promised eventually to pay his mathematician. Kepler left Vienna and went to Augsburg and Nuremberg to try to collect the funds, but because the Empire was caught up in the Thirty Years' War, he never managed to get his money. Eventually he printed the

work at his own and his family's expense, reporting to Brahe's son Georg in 1627 that he had laid out 500 florins for the project.[25] He even bought the paper and took it himself to the print shop in Ulm.[26]

Kepler's frontispiece for the *Tabulae* tells the story of its funding. On the top of the temple of astronomy sits the Habsburg eagle with its imperial wings outstretched and coins falling from its beak on to the astronomers below. Only a few of the eagle's coins, however, have actually reached Kepler's desk – so few, in fact, that he is forced to write on the tablecloth, presumably a reference to his problems purchasing paper.[27] A few coins have also reached the printer's table, an ironic touch since it was Kepler, not the Habsburg Emperor, who paid the printer in the end. Kepler's bold jest at his supposedly beneficent patron is a somewhat bitter reminder of how difficult it was for most natural philosophers to print their books in the early seventeenth century. Even Kepler, mathematician to the Holy Roman Emperor, could not raise the funds for the publication of his most celebrated work and eventually had to finance it out of his own pocket.

Not all natural philosophers had quite as much difficulty publishing as Kepler did; his main patron, after all, was in the midst of a devastating war that threatened the very foundations of the Holy Roman Empire. But equally unusual was the success of the English physician Robert Fludd (1574–1637). When the English parson William Foster (1591–1643) questioned Fludd's motives for publishing abroad rather than in England, Fludd responded with quite a practical answer: 'I sent [my manuscripts] beyond the seas, because our home-borne Printers demanded of me £500 to print the first volume, and to find the cuts in copper; but, beyond the seas, it was printed at no cost of mine, and that as I would wish. And I had 16 copies sent me over, with 40 pounds in gold, as an unexpected gratuitie for it.'[28] This offer from the De Bry printers in Oppenheim was particularly generous, and should be taken as even less typical than Kepler's failure. Fludd and Kepler found themselves on opposite sides of many issues, and their luck in attracting financial support seems to have been no different.[29]

Given his inability to secure funding from his patrons, then, why did Kepler not give up printing the *Tabulae*? They were, after all, mostly Brahe's observations, though Kepler did essential mathematical work to prepare the raw data for the book. So why was Kepler willing to invest so much of his own money and effort in printing the *Tabulae*? Part of his motivation lay in his awareness of how important Brahe's observations were to Europe's community of astronomers. Kepler believed that they were so important, in fact, that after Brahe's death, he simply stole some of the observations rather than leave them to Brahe's heirs, as the will requested, for fear that the heirs could not put them to proper use. He continued to fight legal battles with Brahe's relatives for decades for the right to use the data.[30] Perhaps Kepler knew that, borne by print, the observations would set in motion a transformation in astronomy similar to those he felt the books of Luther and Paracelsus had inspired in religion and medicine in the sixteenth century. His desire to communicate what he viewed as

important information, then, was an essential part of his determination to print the *Tabulae*.

The *Tabulae*'s frontispiece, and Kepler's interpretation of the significance of the tables, reveals another motivation: they were a means of securing his place at the end of a long lineage of astronomers by creating a visual narrative of astronomy's genealogy.[31] The engraving depicts a temple in which the five major figures of ancient and Renaissance astronomy are absorbed in debate. A Chaldean astronomer is hidden in the back of the temple next to a column that looks much like an unfinished tree trunk. Hipparchus and Ptolemy are closer to the front, each next to a slightly more elegant brick column, and Copernicus is seated in the front of the temple beside a refined Doric column. But Tycho is clearly the most advanced of the crowd, as indicated by the ornate Corinthian capital of his column and the diagram of his model of the heavens on the ceiling of the dome.

Kepler does not join his colleagues in this illustrious temple of astronomical progress. The frontispiece appears, at first glance, to be a tribute to Tycho and his contributions to astronomy. A closer look at the image, however, reveals Kepler's subtle presence in the temple. On top of the dome on which the Tychonic system is inscribed stand emblematic figures of the traditional handmaidens of astronomy – geometry, arithmetic and optics – in addition to two new muses particularly central to Kepler's astronomical work, magnetism and dynamics. Even traditional geometry seems to signal that she has become a Keplerian muse by holding an image of an elliptical orbit, an allusion to what became known as Kepler's first law. Although these Keplerian muses depend upon Copernicus' theoretical column and Brahe's observational column for their support, their presence on the top of the temple suggests the triumph of the Keplerian cosmos over the Tychonic.[32]

If the viewer's eye follows the narrative of the frontispiece down to the base of the temple, it would encounter first the Isle of Hven in the centre, the location of the observatory where Tycho observed the heavens. The image of Kepler on the left reinforces the symbolism of the muses above; on his desk is a model of the dome, revealing Kepler's identity as the true architect of the temple's crown. A small plaque in the panel lists Kepler's most significant publications, the *Mysterium cosmographicum* (1597), *Astronomiae Pars Optica* (1604), *Commentariis de motibus stellae Martis* (1609), and *Epitome Astronomicae Copernicae* (1621). The panel on right completes the story of the book's publication, depicting the printer and his assistant producing the book. This narrative of the production of the book, from Tycho's hands, to Kepler's and finally to the printer's workshop, forms the base of the temple of astronomy and suggests the role Kepler hoped the data would play in the foundation of his new astronomy.

Using the various symbols in the frontispiece, Kepler created a visual history of astronomy and carefully placed himself at its culmination. Just as he had used the *Mysterium Cosmographicum* decades earlier to launch his career, Kepler now used another printed book at the end of his life to carefully shape the way

his work was perceived by posterity. Brahe's heirs too understood the power of books to write their authors into history, and engaged Kepler in a series of unfriendly negotiations over how Tycho was to be represented in the printed edition of the *Tabulae*. Aware that Kepler's astronomy diverged on several points from Brahe's, Brahe's son-in-law Tegnagel and later his son Georg Brahe reserved the right to censor the final version of the manuscript. They insisted, for example, that Tycho's name be first in the title and dedication, and that his observations be given proper credit as the foundation of the tables. When the heirs saw the initial sketch for the frontispiece, they demanded that Tycho appear more formally in court attire wearing his long ermine robe and elephant medal (the highest award of the Danish monarchy). They also objected to the title page, which implied that Kepler needed to correct Tycho's data; Kepler had to have it reprinted with different wording. But despite all the heirs' careful attention to detail in an effort to make the book a glorification of Tycho's work, Kepler ultimately prevailed by manipulating the book to present the triumph of his own views over Tycho's.

The frontispiece for the *Tabulae Rudolphinae* and Kepler's earlier use of his *Mysterium Cosmographicum* exemplify the multitude of reasons a seventeenth-century author might choose to bring a book into print. Kepler conceived of his first book as a way to establish his own reputation among contemporaries in the republic of letters and perhaps attract a patron. At the end of his life, he saw the *Tabulae* as a way to write himself into the history of astronomy. In the years between, Kepler produced a number of other books, each with yet another purpose. He intended his textbook of Copernican astronomy, the *Epitome Astronomiae Copernicanae* (1621), to instruct school children and hoped that it would reach 'school benches of the lowest grade'. 'Because one can only learn this knowledge with proper success,' he wrote, 'if everyone who wants to pluck its fruit in the prime of life has tilled its fields as a boy; thus I wanted to come to the aid of all by means of an easily-understandable presentation, low price and fitting edition.'[33] He also produced a number of *ephemerides*, detailed explications of the planets' motions for a single year. These tables, which he produced throughout his life, were intended to be handbooks of astronomical data, practical guides to the heavens. His fanciful *Somnium*, the Copernican tale of a trip to the moon, rounded out Kepler's diverse styles of writing as an early work of science fiction. In his experimentation with genre, Kepler was something of a pioneer for new forms of writing: his work provided models for future scholars who took these genres even further.

Variation in form occurred through the addition of illustrations as well as the style of the text itself. Occult authors, for example, often included in their books highly elaborate and esoteric engravings which illustrated the secrets of nature they claimed to reveal. Because the complex symbolism of these images prevented all but the true initiates from understanding the secrets they offered, these illustrations were a way for occult authors to resolve the inherent contradiction in publicizing occult knowledge. By representing the mysteries of nature

in symbolic graphic form, occult authors could publish powerful secrets without fear that the ignorant masses might use them to dangerous ends.

Like many of his fellow initiates, the occult physician Robert Fludd accompanied his natural philosophies with what are now some of the most well-known scientific images of the seventeenth century.[34] Given the importance of such engravings to occult authors, it does not seem unusual that Fludd sent his works to top engravers in Germany for publication. Johann Theodore De Bry in Oppenheim, as Fludd explained to his opponent Foster, could provide far superior engravings and more generous financial incentives than the English printers. Johann Theodore's father Theodor, a Walloon who left his home town of Lüttich for Frankfurt in 1590 for religious reasons, brought with him the latest engraving techniques from the Netherlands.[35] He and his sons eventually built a successful career in Frankfurt and Oppenheim on their engraving skills. Johann Theodore De Bry published Michael Maier's alchemical emblem book, *Atalanta fugiens,* in 1618, and also designed and printed a number of engravings for Frederick V of the Palatinate's alchemical court in Heidelberg. The De Bry's skills (and Fludd's recommendation) even attracted the English anatomist William Harvey (1578–1657), who published his famous *De motu cordis* with them in 1628.[36]

Historians have explained the De Brys' interest in occult authors by suggesting that they were themselves Rosicrucians.[37] Why a modern figure like Harvey, the 'discoverer' of the circulation of the blood, chose to print with them seemed anomalous. Though they may well have been allied with the Rosicrucian movement in some way, the prevalence of occultists and the presence of Harvey among the De Brys' clientele is much more likely attributable to their engraving skills than anything else. Authors usually chose their printers carefully, and when illustrations were an integral part of the book, as with both occult natural philosophy and anatomy, writers might even decide to send their manuscripts abroad in order to get the best quality engravings.

Decisions such as where to print, whether to use engravings, and how to envision one's public were all an essential part of the author's task. Natural philosophers such as Fludd and Kepler did not simply retreat back to their studies after the manuscript had been delivered to the printer; most remained involved in the printing process at every step, from choosing a printer to distributing the final copies. Again, Kepler's experience with the *Tabulae Rudolphinae* is illustrative of this point. He directed every stage from the project, from start to finish. As we have seen, he designed the frontispiece himself with a careful eye to its representation of the history of astronomy and with a bitter hint at his patrons' lack of financial assistance. The title page of the book tells the reader that the printer even used Kepler's own type for the numbers, since such special characters were often difficult to produce well. After the *Tabulae* were finally printed, Kepler himself traveled to the Frankfurt book fair in 1627 to negotiate the sale of books, and sent copies to his friend Bernegger to sell in Strasbourg. In this monumental project, Kepler had indeed

acted as financier, designer, paper supplier and distributor; he had managed every aspect of the publication with the exception of the actual physical labour of printing the book.

Given this level of involvement, it hardly surprising that shortly after the completion of the *Tabulae Rudolphinae* Kepler took on the role of print master as well. In 1628, he found a new patron in the Emperor's star general, Wallenstein, who wanted to set up a court in his newly acquired Duchy of Sagan in Silesia. Kepler's astrological skills had attracted Wallenstein's attention years earlier, so he asked Kepler to take the job as his personal mathematician and astrologer. Once Kepler settled his family in Sagan, he set out one more time to procure the equipment and personnel for the press Wallenstein had promised him. 'Amidst the collapse of towns, provinces, and countries, of old and new generations, in the fear of barbaric raids,' he wrote, 'I see myself obliged, as a disciple of Mars though not a youthful one, to hire printers without betraying my fear. With the help of God I shall indeed bring this work to an end, in a soldierly fashion, giving my orders with bold defiance and leaving the worry about my funeral to the morrow.'[38] In 1629, after negotiations with printers from Prague and Frankfurt fell through, Kepler found himself with two Prague apprentices, a press from Frankfurt in his basement, but no master printer. 'And so the work of this time necessitates,' he wrote, 'that I myself should be the apprentice prince (as they call the printer master).'[39] In his new role as print master, Kepler spent his final years printing the *Ephemerides* of 1630. His final work, the posthumous *Somnium* (1634), was completed by his son.

Throughout his career as astronomer and author Kepler increasingly blurred the line between author and printer. By the end of his life it was a short step for him to actually become the printer himself. Like Regiomontanus and Brahe before him, Kepler too was motivated to take control of the means of communication so that he might manipulate it to his own benefit.[40] But he was also driven to become a print master out of necessity because the challenges of raising the money, collecting paper in the midst of a war, and finding a properly-equipped press were so great that the only way he could guarantee that his work would make it into print was to do it himself.

Publishing for a living

In the early decades of the seventeenth century printing fuelled the ambitions of many natural philosophers. As we have seen in the case of Kepler, technical supervision of book publication was a standard feature of early modern scholarly life. Authors built presses, provided the wood blocks for illustrations, collaborated on the design of frontispieces and title pages, and even bought the type and paper to ensure that their books would be printed. While some authors involved themselves to this degree due to a personal fascination with a relatively new technology, the majority saw no other means to achieve the goal of publica-

tion. Becoming an 'apprentice prince', as Kepler aptly put it, was the price of authorship.

The extensive demands placed upon authors reminds us how unprofitable most scientific publications were. With the exception of popular medical and astrological works, few scientific books commanded a wide audience. Rarely could one say of a natural philosopher what was said of the Paduan Aristotelian and professor Fortunio Liceti – that he published so many books that the mere index of them would produce another book.[41] Even the introduction of illustrations into works of astronomy, medicine and natural history altered this limited reception only marginally. The enthusiasm of educated book collectors for works of natural philosophy was the exception that proved the rule.[42] Largely educated in the universities, such scholars had acquired a taste for philosophical subjects and commanded linguistic skills, especially knowledge of ancient languages, that placed them in a very privileged sector of the early modern reading public. As long as natural philosophers primarily addressed this audience, they would sell very few books. The struggles of many natural philosophers to publish at the end of the Renaissance eventually led prospective authors to experiment with new forms of scientific communication. Authors such as Kepler, Bacon and Galileo not only tried more popular genres, from the dream to the dialogue to the utopia, but also began to publish in the vernacular.[43] Such efforts, combined with the increased publicity of debates surrounding Copernican astronomy, transformed the scientific book into a more marketable commodity.

Even as Kepler clawed his way into print, other natural philosophers discovered that authorship could bring fame and fortune. In 1610 Galileo proclaimed: 'I should like my books ... to become my source of income.'[44] Prior to 1610, Galileo was virtually unknown as an author of printed works. In Padua, he was known as a mathematics professor reputed to be the author of a satirical dialogue lampooning traditional interpretations of comets and the follies of scholastic philosophers.[45] He had also developed a reputation as an inventor of scientific instruments. By 1606 Galileo enjoyed local renown for his military compass, the reason for his first scientific publication. In summer 1606, 60 copies of *Le operazioni del compasso geometrico, et militare* appeared, printed by Pietro Marinelli 'in the home of the author'.[46] They could be purchased directly from Galileo to accompany his compasses.

The circumstances surrounding Galileo's publications allow us to chart the development of his attitude towards publishing and his changing status as an author. In 1606 he presented himself as reluctant author, forced to publish in order to prevent another – Jan Entel Zieckmesser – from taking credit for his ideas. Knowledge of inventions, he wrote, was best transmitted orally, not only to preserve its secrecy but also because it was most effective when linked to a demonstration of the instrument itself. No printed version could ever capture the full import of such knowledge. 'This indeed would have been a powerful reason for me to refrain from printing this work, had it not come to my ears

that another ... was preparing to appropriate it himself. This made it necessary to insure by printed evidence my labors and reputation against any who wanted to claim it.'[47] As further security, Galileo omitted instructions on how to make his compass, reserving that portion of his invention for private communication.

Publishing one's ideas, however, did not ensure that credit would follow. In 1607 Baldassare Capra produced a Latin plagiarism of Galileo's book, which had been written in Tuscan to please his patrons. Galileo responded not only by having the University of Padua arbitrate the priority dispute, but followed his victory in the halls of academe with a published account of Capra's infamy. By May 1607 all but 30 of the 483 copies of Capra's book had been confiscated. Yet Galileo feared that even this handful of books might cast his authority in doubt, especially outside of the Republic of Venice where the details of the dispute were not well known. His *Difesa contro alle calunnie et imposture di Baldassare Capra* (1607) published all of the university decrees against Capra, firmly establishing his priority as an inventor. As Galileo had begun to discover, the printed word was a powerful weapon with which to create and defend a reputation. From this point onwards, publicizing knowledge became one of his primary goals.

Galileo's next opportunity to publish accompanied another invention – the telescope. This time he considered the nature of the publication carefully. The work would be a slim Latin pamphlet – an 'announcement' (*avviso*) not dissimilar to the newsworthy format used by the merchant Fuggers and by travellers to the Americas reporting marvels[48] – announcing to all of Europe the discovery of four satellites orbiting Jupiter. Using the same printer who had printed his *Difesa*, Galileo rushed the *Sidereus Nuncius* (1610) into print. What care he took with the flowery dedication to the Medici Grand Duke Cosimo II was mitigated by the disastrous state of the printed text. As Galileo apologetically told the Medici secretary Belisario Vinta in March 1610, he had written 'most of it while the earlier parts were being printed', completing the ending as the introduction rolled off the presses.[49] Unpaginated illustrations were inserted at the last minute and Galileo and the printers found themselves pasting *Medicea* over *Cosmica* in the earliest run of this book, in order to correct a mistaken assumption that Cosimo might prefer to have the Jovian satellites named after himself rather than his family. Aware of these problems, Galileo rushed to assure his benefactors that the next edition – promised but never published – would correct all such errors.

Despite the numerous problems in completing and producing the *Sidereus nuncius*, it was a manifold success. By May 1610 the Medici had not only rewarded Galileo with the position of court mathematician and philosopher and a princely stipend but also sent 200 *scudi* to defray Galileo's expenses in printing copies of his work and making telescopes for patrons.[50] The 550 copies of the *Sidereus nuncius* – almost a tenfold increase from the number of pamphlets printed to accompany his military compass – reportedly sold within a week. Many never appeared in bookstores but circulated through courtly and diplo-

matic channels that linked the Medici family to other European rulers. Little wonder that Galileo felt optimistic about the possibilities of professional authorship, since one small, imperfect book had done so much for his career. Virtually overnight he had gone from being self-published to a publishing success.[51]

During the next two decades Galileo's status as an author increased and, with it, the value of his books. Within two years, he no longer performed the mundane tasks of producing his books in the local commercial market of Venice, admittedly one of the best in late Renaissance Europe, but delegated these responsibilities to other people. He published his *Discorso ... intorno alle cose che stanno in sù l'acqua, ò che in quella si muovono* (1612) in Florence, where it was overseen by his friend the Benedictine monk Benedetto Castelli. A year later, he decided to publish his letters on sunspots, *Istoria e dimostrazioni alle macchie solari e loro accidenti* (1613), in Rome. While the recipient of these letters, the Augsburg patrician Marc Welser, would have liked to publish the letters against the Jesuit Christoph Scheiner in Germany, he found the technical difficulties of printing and proofing an Italian text in a German city insurmountable.[52] By June 1612 Galileo determined that his friends in Rome, the members of the Accademia de' Lincei who had elected him to their scientific academy in 1611, should be entrusted with his work.

Founded in 1603 by the Roman noble Federico Cesi and his companions, the Accademia de' Lincei saw publications as an important part of their attempt to reform natural knowledge. The nucleus of the academy was the museum in Cesi's Roman palace, filled with books and other collectibles. Virtually all the noteworthy members of the academy – from the Neapolitan magus della Porta and Galileo to the German physician Johann Faber, the Roman virtuoso Cassiano dal Pozzo and Cesi, who described himself as 'continually thirsty for good books' – were book collectors.[53] Acquiring, reading, editing and writing books, as Silvia de Renzi notes, was an essential part of the Lincean's activities. These principles informed everything from the Lincean discussion of Aldrovandi's natural histories – which they found badly printed and poorly engraved – to their acquisition of key manuscripts such as the remnants of sixteenth-century Spanish physician Francisco Hernández's natural history of Mexico, which they edited and published throughout the first half of the seventeenth century. Publishing successes such as della Porta, one of the most prolific authors of the period due to the phenomenal success of his *Magia naturalis* (1558), and Galileo were admitted *because* of their books, while others such as Bacon were considered for admission as part of the vast reading and collecting program of the Linceans.[54] As Cesi observed, 'the multiplicity of books and printed matter' by the early seventeenth century had created a new world of learning and enhanced the status of authors.[55]

Academy statutes provided for a librarian who would acquire books and facilitate the publishing of Lincean projects. By 1612 Linceans such as Cesi, Francesco Stelluti and the Lincean secretary Angelo de Filiis were fully engaged in the project of publishing Galileo's latest book. Cesi determined the size of the

book (quarto) and print run (2000), closely supervised the engraver, and anxiously scanned the catalogues from the Frankfurt book fair for any works that might compete with their project.[56] In December 1612 the Roman printer Giacomo Mascardi had the first folio ready for proofing. The Linceans sent it immediately to Galileo for his approval, as they did with virtually every aspect of the book's production. Perhaps still smarting from his embarrassment over the appearance of the *Sidereus nuncius*, Galileo responded with a list of 'little errors that escaped the diligent care of the printer'. Among them was a suggestion to the compositor to remove all punctuation from the 'small letters that indicate mathematical figures'.[57] Clearly mathematics was still a specialized language that few printers had mastered, just as shading the sunspots also posed tricky problems for engravers who had not participated in Galileo's observations but were asked to represent them.[58]

All this care did not preclude a few anxious moments as the publication reached its conclusion in March 1613. While the Linceans vacillated about the tone of the preface composed by de Filiis, Galileo gambled that his predictions about the position of the sunspots in March and April would be accurate enough to be worth printing (making the work more immediately useful for spring readers). Concerns about book distribution also influenced the final appearance of the text; when the Imperial ambassador left Rome for Germany in late February 1613, he took with him a number of copies missing the preface.[59] Cesi preferred that the books travel to the Holy Roman Empire through these diplomatic channels, ensuring safe delivery into the right hands, however incomplete the text. Certainly it was better to ensure a good sales and distribution than worry overmuch about the physical appearance of a few books? Having completed the German consignment, he and Mascardi turned to the remainder of the copies. By the time Stelluti loaded them on mules bound for Florence, they had printed a number of copies on 'finer paper' as presentation works for important patrons.[60]

The long process of producing Galileo's *Istoria e dimonstrazioni* convinced the Linceans that they needed to establish regular channels of production and distribution for their books. By January 1615 de Filiis and Stelluti concluded negotiations with Roman booksellers who were, in essence, permanently contracted to work with the Linceans. Financing was surely one of their concerns. While half the copies of the *Istoria e dimonstrazioni* had sold, another thousand languished in the warehouses. Mascardi finally shipped them to Venice, hoping that associates there, more closely tied to the international book trade than their Roman counterparts, would facilitate better distribution.[61] In the meantime, Galileo worked to enhance his reputation – and hopefully improve book sales – by strategically placing copies in some of the new public libraries that one found in various European cities by the early seventeenth century. In July 1617 the librarian of archbishop Federico Borromeo's Biblioteca Ambrosiana in Milan thanked Galileo for his generous offer to provide copies of all his publications to the new library. Since they already had four, only the remaining few were

needed for this 'marvellous library'.[62] Through gifts, booksellers and book collectors, Galileo and the Linceans worked to ensure that his fame would grow and they would profit.

The Catholic Church's condemnation of Copernicus's *De revolutionibus* in 1616 cast a temporary pall over the enthusiastic publishing projects of the new science, which increasingly advocated heliocentrism after Galileo's publications on the Jovian satellites and sunspots. Certainly this was one of the reasons why Galileo's controversial advocate, the Dominican Tommaso Campanella (1568–1639), published his philosophical and political works outside of Italy after 1617, first with the Lutheran Tobias Adami in Frankfurt and later in Paris. As he remarked to the Medici Grand Duke Ferdinando II, upon the re-publication of his *De sensu rerum et magia* in Paris by Louis Boullenger in 1636, he felt that he had been providentially expelled from Italy in order to find greater opportunities to publish his ideas.[63]

Campanella had been nurtured in the politically and philosophically explosive environment of Naples, which had produced printer-authors such as the Lincean Nicola Antonio Stigliola. Both a friend of the heretic Giordano Bruno (1548–1600) and fellow prisonmate of Campanella in the late 1590s, Stigliola had his *stamperia a Porta Regale* (f.1592) closed by the Inquisition in 1606. Even afterwards he continued to publish clandestinely, bringing his own *Encyclopedica Pythagorea* (1616) to light with the help of Constantino Vitale.[64] With such unorthodox companions in his youth, it was hardly surprising to find Campanella willing to employ the Lutheran Adami for the printing of his *Apologia pro Galilaeo* (1622), which appeared in Roman bookshops by January 1623. Alluding to the current theological controversies about astronomy and philosophy, Adami wrote in his preface: 'it is no small matter to engage in grave disputes about the structure of the world.' Yet it was potentially quite profitable to publish them; when the French ambassador to Venice asked Paolo Sarpi how to acquire a good library, Sarpi replied that buying all the books on the Index of Forbidden Books was the best way to proceed. In a similar spirit, Adami concluded his address to Campanella's readers by exhorting them to 'look for more writings by this author soon'.[65] By January 1623, Campanella's *Apologia* was on the Roman Index.

While Campanella resorted to blatant and often ecstatic unorthodoxy, putting his works in the hands of a heretic, Galileo and the Roman Linceans preferred to be more circumspect. The same year that Campanella's *Apologia* appeared, they were in the midst of assisting Mascardi complete the printing of Galileo's *Il Saggiatore* (1623). It was a triumphant salvo in a debate about the nature of comets conducted with the Jesuit Orazio Grassi, whose *De tribus cometis anni MDCVIIII disputatio astronomica habita in Collegio Romano* (1619), published anonymously with Mascardi, had precipitated it all.[66] Enjoyed by no less a figure than Urban VIII, to whom it was dedicated and whose delight in hearing it aloud spurred many courtly readings of the *Saggiatore*, the book further solidified Galileo's fame.

As with the *Istoria e dimonstrazioni*, the *Saggiatore* was a collaborative editorial project of the Linceans that moved quickly to its conclusion. Begun in May, the printing was completed by August 1623. All that remained to finish the book were the engravings and the frontispiece. Part of the speed undoubtedly derived from the widespread manuscript circulation of the *Saggiatore* in Rome, where it had been vetted by papal courtiers and academicians friendly to the cause of the Linceans. Yet the decisive factor in expediting publication was the election on 6 August of Maffeo Barberini to the pontifical throne as Urban VIII. Six days later, Stelluti asked Galileo's help with the design of the frontispiece. By the time Galileo sent a sample cover from Florence the following month, Cesi and his associates had already commissioned a design in Rome that would link their academy, Galileo's publication and the new papacy in one glorious union. In early October Galileo approved the design, requesting only that the printer add an 'and' between the words 'astronomical' and 'philosophical' so that his description of Grassi's pseudonymously published *Libra astronomica ac philosophica* (1619) would be accurate.[67] [see plate 6]

The burdens of having the *Saggiatore* coincide with Urban VIII's ascension to the papal throne put enormous pressures on the book. When Virginio Cesarini sent Galileo the first copy on 28 October 1623, he apologetically wrote: 'The impression of your book has been finished with the greatest accuracy that the haste of printing allowed.' As if to confirm this assessment, that same day Stelluti wrote to inform Galileo that they were redoing one page because the figure (car. 121) had been printed badly.[68] As if to compensate for the hastily composed contents, Cesi lavishly bound and decorated 60 copies at his own expense to present to cardinals, papal courtiers and the Roman nobility. By November the rest were on their way from Mascardi's shop to all the principal cities in Europe where books were sold. This breathless pace left everyone in Rome exhausted and perhaps just a little more cynical about the meaning of publishing one's ideas. As Cesi later confessed to Galileo in 1627, 'The labour of printing ... presses more than ever ...'.[69] In the midst of all this activity, the publication of Hernández's *Rerum Medicarum Novae Hispaniae Thesaurus* (1651) fell further and further behind.

Two weeks later, Galileo composed and printed in Florence an *errata* sheet, which he sent to important patrons such as Borromeo, lamenting the 'negligence of the proofreader'. He further urged his fellow Linceans to insert it into copies of the *Saggiatore* in Rome. Despite the sloppy production of the book, the book collector Borromeo assured Galileo that it would enjoy a 'principal location in our Ambrosian Library'.[70] Galileo again had achieved much through expediency. Instead Grassi's subsequent response, *Ratio ponderum librae et simbellae* (1626) languished for two years in the hands of a Paris printer. As the Father General of the Society of Jesus, Muzio Vitelleschi, explained to Grassi in July 1626, 'I believe that it is not due to the lack of diligence on the part of the Fathers, but to the Printers to whom the author's presence usually creates a sense of application, etc.'[71] Timing was not on the Jesuit's side.

A few years later, Galileo found himself in a similar predicament. Having completed the manuscript of his *Dialogo sopra i due massimi sistemi del mondo, Tolemaico e Copernicano* (1632), he found himself bereft of Cesi's publishing expertise, due to the prince's untimely death in 1630. Castelli recommended printing in Florence, though the Linceans preferred Rome; Galileo thought of Venice but the political timing was awkward and the onset of plague severely disrupted commerce between different regions of Italy. He briefly considered Genoa only to discover that personnel was in short supply: there was a printer there willing to undertake his work, friends told him, but Galileo would have to provide 'someone to operate the press, and another to compose characters, in addition to a proofreader'.[72] Finally he took Castelli's advice, making an agreement with the Florentine printer Giovanni Battista Landini for the publication of 1000 copies. Without his normal circle of associates to assist him, Galileo found himself back in the 'workshop of the bookseller', arranging for the distribution of his book through associates in such cities as Rome and Bologna. He, rather than the Roman Linceans, paid for the binding and decoration of gift copies for patrons in May 1632, three months after its publication.[73] By August Landini found his books confiscated by the Florentine Inquisiton; in October Galileo was ordered to Roman to stand trial for advocating Copernicanism in print. Abjuring his heresies in June 1633, in Rome, he was condemned to permanent house arrest in his country villa at Arcetri for the remainder of his life.

The process by which Galileo's *Dialogo* was examined, approved for publication and then condemned has been well told elsewhere, so there is no need to repeat this story.[74] As Robert Westman writes in his study of extant copies of the work, 'the *Dialogue* was not only a book with new arguments but it was a new *kind* of book, aimed directly at a constituency of men whose principal concerns were not academic disputations but cultivated and polite learning.'[75] As with the *Saggiatore*, it was designed as a witty and elegant account of the differences between ancient and modern astronomy, cast in the form of a dialogue that evidently gave the 'moderns' the upper hand. Those readers who managed to secure copies prior to the confiscation of the book consumed it greedily, correcting 'printing errors', as the Bishop of Pistoia told Galileo on 26 May 1632, and enjoying the occasionally polemical marginalia and provocative jokes at the expense of the Aristotelians.[76]

Increased murmuring in Rome against the *Dialogo* initially did not stop Galileo and the printer from distributing it. Galileo's fellow Lincean, cardinal Francesco Barberini, nephew of Urban VIII and an inquisitor in the 1633 trial, complained in late September 1632 that they continued to circulate the *Dialogo* 'as if they were under some dispensation'. By the winter this was no longer the case. Even as Galileo faced the very real possibility that he might be branded a heretic, he continued to worry about the success of his book. He complained to his Parisian correspondent Elia Diodati:

> The bookseller who printed it exclaims that this suspension so far has cost him a profit of 2000 *scudi* because in addition to the 1000 volumes he printed, he could

> have reprinted twice that number. And I, besides my other troubles, suffer this greatest one: to be unable to prepare my other works, especially that one on motion, so as to bring them forth in my lifetime.[77]

From such confidences, one might easily conclude that Galileo's greatest fear in the midst of his trial was not the imperilment of his soul but the potential setback it had caused in his publishing ventures and their profitability. Even in front of the inquisitors for the Holy Office, Galileo could not resist presenting himself as a successful author. As he stated in his deposition of 12 April 1633, he refused 'profitable offers from France, Germany and Venice' in order to allow the Master of the Sacred Palace to monitor more carefully the production of his book.[78]

Just as Sarpi had suggested to the Paris ambassador, prohibiting Galileo's book ensured its success. Scarce copies became valuable collectibles and by 1635 a Latin translation had been prepared in Strasbourg by Kepler's friend, the Protestant historian Martin Bernegger, with the assistance of Diodati. In a letter of 9 June 1634, Bernegger suggested that a modest 600 copies be printed, 'the subject matter being to the taste of few'.[79] Half were sent to Paris, where the French savant Marin Mersenne acquired a copy from a bookseller; others went to such cities as Lyon, Amsterdam and London, where book distributors such as Galileo's kinsman Roberto Galilei and the powerful Elzevier publishing family circulated copies. Those that did not sell by April 1636 were displayed at the Frankfurt book fair by the Elzeviers along with Campanella's *Apologia*.[80] The clandestine book market even ensured Galileo's receipt of copies of his book while under house arrest, since Roberto in Lyon sent copies to the port of Livorno under the name of Signor Balì Ciolli.

During this period Galileo recommenced work on his other great dialogue – *Discorsi e dimonstrazioni matematiche intorno a due nuove scienze attenenti alla mecanica & i movimenti locali* (1638). He also began to consider the idea of reprinting his earlier works, quickly discovering that the long arm of the Inquisition effectively ensured that he could never again publish in Italy. By 1635 friends in Paris supported the idea of creating an *Opera Omnia*, to Galileo's great enthusiasm. Both projects required the involvement of Louis Elzevier, whose Amsterdam firm (f. 1638) became the principal publishing centre of the Elzevier family in the mid-seventeenth century.[81] In May 1636, Elzevier visited Galileo in exile at Arcetri to confirm their plans to publish the *Discorsi*, which subsequently arrived, one day's worth of dialogue at a time, through intermediaries in Venice. Informed of Elzevier's enthusiasm at the prospect of publishing Galileo's collective works, the Florentine mathematician responded immediately that he hoped for 'a magnificent folio volume'.[82] He assured his would-be publisher a guaranteed profit since all of his books were out-of-print and increasingly collectors' items – sold at 'four and six times the ordinary price'. In this fashion, Galileo constantly reminded his correspondents that publishing his works transcended the perils of ordinary authorship.

The technical details of publishing seemed increasingly important to Galileo in his final years. Both the physical appearance and legal status of his works mat-

tered very much to him. From the Elzeviers, he secured a promise that they would create a better frontispiece for his *Discorsi* than Brunegger had for the Latin translation of the *Dialogo* (ultimately they did not because Galileo's title page did not arrive on time). Confiding in his Venetian friend, the cleric Fulgenzio Micanzio, he worried that the inclusion of the *Dialogo* in his collected works would place all of them on the Index, and suggested its omission; he considered how to add new material to his complete works so that publishers could obtain a new licence, ensuring better profit.[83] Yet at the same time, it was also apparent that Galileo had become a publisher's nightmare. Failing eyesight, other health problems and the usual difficulties of moving goods between Tuscany and the Netherlands greatly slowed the completion of the *Discorsi*. The Leiden printers Bonaventura and Abraham Elzevier, who assisted their kinsman in publishing Galileo, complained about excessive abbreviations and wondered if the fifth book on sound would ever appear (it never did). In March 1638, Louis Elzevier was still trying to coax the conclusion and final corrections out of Galileo. By the time he wrote the preface to the readers, praising the growth of mathematical sciences in the early seventeenth century, he must have been relieved to move on to new authors such as Bacon, Thomas Hobbes (1588–1679), Pierre Gassendi (1592–1655), René Descartes (1596–1650) and Christiaan Huygens (1629–90), many of whose books also took shape in the printing rooms of the Elzevier operation.[84]

Elzevier's waning interest in publishing Galileo was not immediately apparent to the author. In May 1637, Galileo confidently wrote: 'in Leiden, those Elzeviers, the most famous printers in Europe, work for me ...'.[85] Yet this was not exactly the case. Galileo's constant assurances of profit notwithstanding, no publisher would undertake his project without tangible proof that profit could be made. By June 1640 Galileo's Parisian friend Diodati reluctantly informed him that plans for his collected works would be deferred until more copies of the *Discorsi*, the *Letter to the Grand Duchess Christina* and possibly the Latin dialogues were sold 'since 500 exemplars of each still remain'.[86] Apparently the admiration of singular book collectors such as the Venetian Francesco Duodi, who asked Galileo's assistance in acquiring copies of his books ('the prohibited one as well as the others'), was not common enough to make his latest publications immediate bestsellers. 'I will not spare any expense putting them together, valuing them like a jewel,' declared Duodi in 1639.[87] As a result, the 1640 Paduan reprint of Galileo's little pamphlet on the military compass and the 1641 Lyon reprint of the Latin dialogues brought the author no profit.

In the dedication of his *Discorsi* Galileo presented himself as a reluctant author in his final years. 'The disappointment and discouragement I have felt over the ill-fortune which has followed my other books are already known to you. Indeed, I had decided not to publish any more of my work,' he wrote to the Count of Noailles.[88] However, the image of unintended authorship which Galileo carefully presented in print after the 1633 condemnation was far from true. As has been apparent from the preceding discussion, Galileo worked carefully and consistently to establish relations with printers, distributors and booksellers

throughout Europe in order to immortalize his words. From Rome the owner of the *del Sole* bookstore, who played a famous role in distributing his most controversial works, traveled north to pay Galileo homage in Arcetri – one of the many associates with whom he maintained long and fruitful relations in the dissemination of the new astronomy and mathematics.[89]

Surely Galileo's care about these matters and his boldness in the face of ecclesiastic censure exceeded the efforts of many of his contemporaries. By the end of his life Galileo had invested a great deal of his income into various publishing ventures, leading one friend, Giovan Michele Pierucci, to comment: 'you instead spend rather than earn, and spend a lot.' Criticizing printers who made a profit from publishing Galileo, Pierucci marveled that they did not appreciate 'the great glory that their print houses are honored and legitimated by the work and name of the first author of the century.'[90] Ironically personal profit had been sacrificed in the service of fame. But profit clearly *was* there to be made, notwithstanding the protests of printers. In 1655–56 the collected works of Galileo finally appeared. Not until the mid-eighteenth century did the Holy Office authorize any re-edition of Galileo's writings, finally putting their imprimatur on the 1744 Padua edition of the complete works edited by abbot Giuseppe Toaldo.[91]

Producing scientific knowledge

Galileo's experiences foreshadowed those of many other natural philosophers by the middle of the seventeenth century. Concerned about reprisals from the Catholic Church after the 1633 condemnation, Descartes delayed publication of his great new philosophical system, modestly entitled *Le Monde* (published posthumously in 1664), cautiously releasing the vast majority of his ideas in small treatises printed in the Netherlands, away from the immediate jurisdiction of the Inquisition. By 1663, they were on the Index anyway, along with many other works professing new and controversial ideas about nature that did not accord with scripture. Within this same climate, in the early 1660s a member of the Florentine Accademia del Cimento (1657–67) penned the following warning as a reminder to the editors of the *Saggi di naturali esperienze fatte nell'Accademia del Cimento* (1667): 'It is dangerous to make original conjectures ... So look at it again before giving it to the printer.'[92] While some regions such as Spain placed virtually no natural philosophical works on their version of the Index, censors in Italy and France paid increasing attention, in the wake of Galileo's trial, to how one should interpret nature. As Ugo Baldini demonstrates, after 1633 Jesuit censors increasingly limited speculations in Jesuit scientific publications that delved into the more dangerous realms of astronomy and cosmology or, more generally, proposed novel doctrines.[93]

Philosophical ingenuity, however, was not the only measure of scientific publications. From the 1630s through the 1670s, the German Jesuit Athanasius

Kircher (1602–80), professor of mathematics at the Collegio Romano, produced approximately 40 works totaling some 54 printed books. Published by 36 printers scattered throughout Italy, Germany, France and the Netherlands, often in multiple editions, these lavishly illustrated encyclopaedias were the delight and bane of the Baroque reading public. Few equaled Kircher's prolific record; among his contemporaries, only the English nobleman Robert Boyle (1627–91), whose financial resources rivalled even the ample coffers of the Society of Jesus and its patrons, published more.[94] As a result, Kircher became one of the most sought-after philosophical authors in mid seventeenth-century Europe. Knowing that he enjoyed steady papal and imperial patronage from Rome and Vienna that surely helped to defray the exorbitant cost of his lavish folio illustrations, printers vied for his business.

A number of Kircher's early works belong to the large and mostly unstudied genres of scholastic publication that emerged from the Jesuit colleges and European universities.[95] Increasingly, however, Kircher's writings reflected his antiquarian and philosophical interests in ancient Egypt and the eclectic experimental culture of his museum in the Collegio Romano, both addressing a broader, more heterogeneous audience. Roman printers such as Ludovico Grignani and the Lincean printer Vitale Mascardi published such important works as his *Ars magna lucis et umbrae* (1645), *Oedipus Aegyptiacus* (1652–54), and the third and final edition of his *Magneticum rerum naturae* (1654), the culmination of Kircher's many publications on universal magnetism. During the 1630–50s he remained fairly loyal to his Roman publishers, undoubtedly due to their profitable connections with his Barberini and Chigi patrons and possibly his Jesuit superiors. His primary exception involved the publication of his *Musurgia universalis* (1650), the first part of which was published in Amsterdam by Jan Jansson and the second part in Rome by Grignani. The rapid success of this book, printed in about 1500 copies and distributed not only in Europe but also through the Jesuit missionary network which placed copies in Africa, Asia and America, led Louis Elzevier to attempt to woo Kircher away from Jansson and his Roman competition.[96] He did not succeed.

Perhaps because of Elzevier's interest, Kircher secured increasingly favourable terms with Jansson. Between 1665 and 1679 Jansson and his associate Elizeus Weyerstraten printed eight of his works, not including their publication of Gioseffo Petrucci's defence of Kircher's philosophy against his critics, Giorgio de Sepi's catalogue of the Collegio Romano museum and Johann Kestler's compilation of Kircher's best experiments.[97] Occasionally the difficulties of transporting materials between Rome and the Netherlands, particularly during times of plague and political unrest, persuaded Kircher to publish elsewhere. But on the whole he remained remarkably loyal to the man whom he described in 1675 as the 'famous printer of Amsterdam'.[98] Jansson had proved as constant as Kircher's Roman printers, producing books with even higher quality illustrations than those in Rome and publishing multiple editions of his highly successful *Mundus subterraneus* (1664). In return, Kircher had the pleasure of becoming one of the

few natural philosophers to be translated into Dutch in order to reach a vernacular audience who could not appreciate his Latinate erudition.[99] Very quickly book collectors gave his works the status of other highly engraved encyclopaedias such as the writings of Aldrovandi and Fludd. Despite the high price of his books, about 50 shillings in England, bibliophiles such as Henry Oldenburg and Samuel Pepys acquired copies. By the late 1670s Hooke owned both *China illustrata* and *Mundus subterraneus*, acquiring the latter at half-price at auction. The former he bought in loose sheets from a bookseller, a typical means of purchasing books at the time, and had his niece Grace bind it in their rooms at Gresham College.[100]

During the period of Kircher's publications encyclopaedic writings continued to enjoy popularity. The French scholar Pierre Gassendi, who participated in the critique of Aristotelian philosophy and the revival of atomism, found enough of an audience for a Lyon printer to print his six-volume *Opera Omnia* in 1658. Chemical philosophers such as Johann Rudolf Glauber (1604–68) and the Paracelsian physician Johann Baptista van Helmont (1579–1644) also had their complete works published, in Glauber's instance twice in his own lifetime.[101] At the same time, textbooks synthesizing the new state of knowledge began to appear with greater frequency. The German Jesuit Caspar Schott (1608–66), for example, combined accounts of his own work with that of his mentor Kircher and the inventor of a series of new vacuum experiments, Otto von Guericke (1602–86); Schott's *Physica curiosa* (1662), an enjoyable and eclectic account of early modern experimental physics, appeared in four editions by the end of the century.[102]

By contrast, Nicolas Lémery's *Cours de chymie* (1675) reflected his practical experience in teaching and revising the emerging discipline of chemistry. This sort of vernacular textbook anticipated the more accessible format of eighteenth-century scientific books which popularized knowledge; it was almost immediately translated into English, German, Italian and even Spanish as well as appearing in a Latin edition that could be used by university-trained scholars.[103] From such information we can conclude that at times the market for scientific and medical textbooks was broader than the audience for controversial authors such as Galileo, since these works served more practical ends. This was surely true to an even greater degree with practical treatises on arithmetic and geometry which addressed a broad range of computational needs. By contrast, important works such as John Wallis' *Arithmetica infinitorum* (1655), a crucial work in the development of differential calculus, belonged to the world of specialists.

During the 1660s many important new forms of scientific publication emerged from scientific academies and societies, such as the Accademia del Cimento in Florence, the Royal Society in London and the Paris Academy of Sciences. Such organizations transformed not only the format in which one wrote but the very idea of scientific authorship. Despite the continued popularity of encyclopaedias and textbooks, shorter treatises and pamphlets began to play an important role

in scientific publishing. The French philosopher and mathematician Blaise Pascal (1623–62) published his *Essai pour les coniques* (1640) as a broadside – a format later used to great effect by early members of the Paris Academy of Sciences such as Giovan Domenico Cassini. In Florence the physician Francesco Redi (1626–97), a figure who played an important part in the culture of the Galilean Accademia del Cimento, wrote his experimental accounts on everything from poisonous snakes and sympathetic medicines to human parasites and spontaneous generation in the form of letters.[104] His most famous work, *Esperienze intorno alla generazione degli insetti* (1668) ran to five editions in two decades, while a number enjoyed Latin, English and French translations. Part of the appeal of Redi's work was due to its format: he succeeded in combining Galileo's witty and elegant literary style with the brevity and clarity of an experimental report, allowing multitudes of readers to replicate his experiments without any difficulty.[105]

To the extent that the scientific encyclopaedia continued to thrive within the new academies, it did so as a *corporate* project undertaken by a group of scholars rather than by an individual. This was precisely what Bacon had suggested in works such as the *Great Instauration* (1620); he hoped to persuade scholars to collaborate in the study of nature, making observation more systematic and the resulting publications both comprehensive and closer to experience. The Lincean publication of Hernández's natural history of Mexico is an early case in point. Beginning with a series of manuscripts brought from Madrid to Italy by the Neapolitan imperial physician Leonardo Antonio Recchi, the Linceans scrupulously edited and re-edited Hernández's work, even sending one of their members to Spain to consult the originals. By the time the second and final edition of the 'Mexican treasure' appeared in 1651, it included many parts of the great project of natural history envisioned by Cesi and his academicians, including numerous observations on animals and plants done by the Linceans themselves and Cesi's attempt at classification, the *Tabulae Phytosophicae*.[106] By then, however, the academy itself had been extinct for 20 years, leaving behind an incomplete encyclopaedia which existed solely in its fragmentary publications.[107]

After the gradual erosion of the Lincean's dream of a new natural history, it took several decades before another group took up the challenge of publishing together. In 1657 several physicians, mathematicians and virtuosi began to meet in the rooms of Prince Leopoldo de' Medici in Florence. Their tests, employing a variety of new scientific instruments, from air-pumps to barometers, eventually appeared as the *Saggi di naturali esperienze*. From the start, Leopoldo imagined that his informal academy would publish its results and managed the end product very carefully. The young Medici courtier Lorenzo Magalotti was assigned the task of writing the book, which he did in multiple drafts that reflected the extensive editorial intervention of other members. Leopoldo, for instance, took such an interest in the Cimento's publication that he would not even let the engraving of illustrations commence when he was away from Florence in 1662.

By 1664 the Cimentans had acquired 'four boxes of the best paper' and permission to publish from the Holy Office in Florence,[108] yet it took two more years for even the title page to appear. Preoccupied almost to the point of despair about the successful conclusion of this project, Magalotti obsessed about decisions as crucial as the placement of the Grand Duke's portrait and the index, and as peripheral as the criteria by which to select commemorative poems. Unlike Galileo, he would not author a book in haste, precisely because it was *never* his book but more directly a project of a Medici prince.[109]

Having finally succeeded in establishing the text and producing appropriate illustrations of the Cimento's instruments, Magalotti coped with the loss of several plates and the inversion of others during printing by the Florentine printer Giuseppe Cocchini. Such problems led him to commission the engraving and printing of the Grand Duke's portrait in Rome, since a botched image of a patron would not do. 'An engraving of such fineness must on no account be entrusted to the awkward skills of these men of ours,' he proclaimed.[110] Even the successful completion of all the different parts of the book and their reunion in Florence did not quell his fears. Magalotti nervously watched the printer ink all 800 copies onto the three different types of paper – 'royal', 'friars' and ordinary – specified to match the relative glory of different recipients of the book; he gave the binder special instructions to rectify further printer's errors in the final composition of the *Saggi*.[111] Distributed as gifts rather than in the marketplace, the Medici essays were an outstanding example of the uses of scientific publication as an expression of princely honour.

One copy of the *Saggi* travelled to London from Florence in 1668 in the hands of Magalotti as part of a diplomatic visit between the Medici and Stuart courts to be presented to Charles II and his recently formed Royal Society. By then, the Royal Society had established itself as a leading centre for experimental learning which sponsored, officially and unofficially, a series of influential publications. Like a number of early scientific societies, this included a journal that printed selected communications to and by the Royal Society.[112] At the same time, the Society continued the tradition of facilitating books by members that would reflect the glory of their endeavours. Following the appearance of important works in England such as the posthumous publications of Bacon, William Harvey's *Exercitationes de generatione animalium* (1651), Walter Charleton's *Physiologia Epicuro-Gassendo-Charltoniana* (1654) and Robert Boyle's *New Experiments Physico-Mechanicall, Touching the Spring of Air and Its Effects* (1660), members of the Society wished to send a strong message to the natural philosophical community that novel interpretations of nature emanating from England would be firmly identified with the Royal Society by bearing its imprimatur. By 1663 they had selected John Martyn and John Allestry as the official printers of the Society, in compliance with their royal charter which gave them the right to license and publish books, including the selection of printers, engravers and ultimately stationers.[113]

Within two years, founding members John Evelyn (1620–1708) and Robert Hooke had published respectively *Sylva: or a Discourse of Forest-Trees* (1664) and *Micrographia* (1665). When Evelyn sold over 1000 copies of his *Sylva* in under two years, booksellers expressed amazement that a work so bulky should do so well – and rushed to gain republication rights. Publishing acumen seems not to have been a forte of the Royal Society, which did not benefit from the profit of such sales. In 1679, as the third edition appeared, Evelyn commented dourly that the 'avaricious printer' Martyn had reaped the rewards while returning nothing to the Society for whom he worked. 'It is apparent that near £500 has already been gotten by it; but we are not yet economists.'[114] Possibly they did better with Hooke's *Micrographia*, the first extensive study based upon microscopic observations, which enjoyed a second edition by 1667. Initially a project assigned to the architect Sir Christopher Wren, it ultimately fell to Hooke as curator of experiments. In 1663 the Royal Society Council commanded that Hooke produce 'a handsome book' that recorded the work of the new scientific society. Edited and revised in a fashion similar to the Cimento *Saggi*, the *Micrographia* differed in one important respect: ultimately it was presented as a book *by* a Royal Society member rather than by the Society itself. Instead the Society licensed and printed it, leaving Hooke to obsess over such details as the placement of letters on the illustrations and the accuracy of the engravings in relation to his own descriptions.[115] [see plate 8]

Possibly the unanticipated successes of these early publications made the Royal Society overconfident. Additionally they cut a smart deal with John Graunt, whose *Natural and Political Observations ... Made Upon the Bills of Mortality* (1664) ran to four editions in two years: Graunt deposited 50 copies with the Society and in turn received an offer of membership.[116] The late 1660s and 1670s yielded a flurry of new publishing initiatives, from Thomas Sprat's *History of the Royal Society* (1667) to the Bolognese anatomist Marcello Malpighi's *Dissertatio epistolica de bombyce* (1669) and *Anatome plantarum* (1675 and 1679) and Nehemiah Grew's *The Anatomy of Vegetables* (1672). All reflected the strong commitment to natural history on the part of the Royal Society; as Oldenburg promised Malpighi, his anatomy of the silkworm would be published 'in splendid style.'[117] Little wonder that continental authors soon clamoured to be published in England, signalling a shift from an earlier period when Fludd had preferred Flemish and German printers.

Publishing natural histories put a heavy financial burden on the Royal Society, just as it had done to Aldrovandi at the beginning of the century. By 1673 the Council had already begun to wonder how it would finance Grew's (1641–1712) further publications in the realm of botany, which they had promised to sponsor. They conceived of the novel idea of financing his works through subscriptions, which ultimately led to the publication of Grew's important *The Anatomy of Plants* (1682) and *Musaeum Regalis Societatis* (1681), a catalogue of the curiosities in the Royal Society's cabinet. Having been forced to hawk his words to fellow members such as Boyle, with the ready cash to finance publica-

tions, and finally to accept even smaller contributions in the coffeehouses of London, it is little wonder that Grew was disillusioned with the world of print by the time he brought his work to completion. 'I am now about to print one more Book,' he wrote to the naturalist Martin Lister in 1682, '& then it will be time to have done.'[118]

One of the reasons the Royal Society forced Grew to sell his ideas in the marketplace regarded their greatest publishing folly of the 1670s and 80s: John Ray's (1627–1705) posthumous edition of Francis Willughby's *Historia piscium* (1686). Having agreed, after Willughby's untimely death in 1672, to underwrite the expense of the natural history of fishes, the Society watched in horror as costs to produce lavish illustrations and lengthy text mounted to £400. This generous decision, surely made because Willughby's widow had underwritten the expenses of illustrating not only Willughby's *Ornithologia* (1676) but also the first part of Ray's monumental *Historia plantarum* (1686–1724), nearly bankrupted the Royal Society. In 1686–87 the Society was so hard up that it paid Edmund Halley his honorarium of £50 in 'fifty books in fishes' and threatened to do the same with Hooke's stipend.[119] As they learned to their chagrin, publishing natural history rarely paid. After the Willughby fiasco and the continued expense of underwriting Malpighi's anatomical publications, the Royal Society no longer offered direct financial support of any projects but instead encouraged members to rely on individual sponsorship, subscriptions and even lotteries to publish.

The financial realities of publishing natural philosophy in Restoration England led Royal Society members to make a variety of different choices. Wealthy natural philosophers such as Boyle could afford to publish original works in English and subsequently pay for Latin translations so that his ideas might reach the eyes of continental philosophers. The results were noteworthy: between 1659 and 1700 John Harwood has counted over 80 editions of Boyle's 42 books and numerous papers, with more than 100 Latin translations.[120] Boyle's munificence extended beyond self-financing to underwriting publication costs for many of his fellow members. As Adrian Johns argues, 'The printing of experimental philosophy may at first have been largely financed by Boyle, who was by far its wealthiest serious propugnant.'[121]

Boyle's self-consciousness about the medium of print led him to manage many aspects of his publications, with the assistance of Oldenburg who essentially performed the services of editor and publisher. It was Oldenburg who responded to continental printers whose unauthorized translations of Boyle's works produced numerous mistranslations and crucial inaccuracies such as the misdating of his experiments, offering adversaries ammunition for their claims to priority in experimental matters.[122] Similarly Oldenburg became a publicist for Boyle's work. Beginning in 1665, in Boyle's *Experimental History of Cold* (1665), Oldenburg listed books 'not yet publish'd, but ... by divers of the Curious expected.' Traditionally such lists had been the printer's prerogative, though Kircher also produced similar broadsheets announcing his works to the

reading public. Competition to publish and translate Boyle's works gave the lists new meaning. By the time Oldenburg composed 'An Advertisement of the Publisher to the Reader Before the Latined Edition', in Boyle's *A Continuation of New Experiments Physico-Mechanical ... The Second Part* (1680), his task was to create an authoritative chronology of Boyle's writings in response to the confusion engendered by unauthorized translations and plagiarism.[123]

The difficulties of managing one's reputation in print plagued many an early modern natural philosopher. While Boyle's response was to publish more, Isaac Newton instead withdrew from the public eye for long periods of his career precisely to avoid such controversies. 'I do not love to be printed upon every occasion,' he told the royal astronomer John Flamsteed in 1699.[124] In many respects, Newton was one of the most self-conscious critics of the role of publication in intellectual life. On many occasions during his tenure as Lucasian professor of mathematics at Cambridge, he declined opportunities for authorship. 'For I see not what there is desirable in publick esteeme, were I able to acquire & maintaine it. It would perhaps increase my acquaintance, y^e^ thing, w^ch^ I cheifly study to decline,' he wrote to John Collins in 1670. Two years later, bruised from the controversies with Hooke, Huygens and other continental philosophers over his 1672 optical paper in the *Philosophical Transactions* – 'that little use I have made of the Presse', as he called it – Newton resolved not to publish further until his ideas were fully weighed and tested.[125] He was true to his word. His two great works, *Philosophiae naturalis principia mathematica* (1687) and *Opticks* (1704) were many years in the making. [see plate 7]

Publishing Newton's *Principia*, arguably the greatest work by any Royal Society member, should have been a moment of triumph for the Society. Instead it occurred in the midst of an acute financial crisis that finally led its members to conclude that their task was to offer an *imprimatur* to worthy authors rather than the actual funds to publish. In May 1686 the Council authorized Edmund Halley to print Newton's work with the Society's approbation 'at his own charge'. It was Halley rather than the Royal Society who earned Newton's thanks for 'his solicitations' in the preface to the *Principia*. Unlike Boyle, Halley had few funds of his own – he primarily published his own works as a series of 81 articles in the *Philosophical Transactions*[126] – but he did have great initiative. Using his Grub Street connections, he made an agreement with the printer Joseph Streater, well known for his quasi-pornographic as well as philosophical publications in London, to undertake Newton's *Principia*, and began the process of coaxing the manuscript out of the hands of a reluctant Cambridge don.

Persuading Newton to finish and to establish the final version of the text was no easy task. As Newton had told Flamsteed in 1685, 'Now that I am upon this subject, I would gladly know ye bottom of it before I publish my papers.'[127] Especially vexed was the inclusion of Book III, the philosophical explanation to accompany Newton's mathematical reasoning of his new system of the world. When Halley discovered that Newton planned to omit this section, he wrote anxiously to him to argue for its inclusion, not just as a friend but as his

publisher who needed to make a profit. '[T]he application of this Mathematical part, to the System of the world; is what will render it acceptable to all Naturalists, as well as Mathematicians,' he informed Newton on 7 June 1686, 'and much advance the sale of ye book.' In an uncharacteristic display of generosity (and perhaps acknowledging that Halley had a point), Newton responded on 20 June: 'The two first books without the third will not so well-beare ye title of *Philosophiae naturalis Principia Mathematica* & therefore I had altered it to this *De motu corporum libri duo*: but upon second thoughts I retain ye former title. Twill help ye sale of ye book wch I ought not to diminish now tis yours.'[128] The first edition sold briskly, even at the high price of 9 shillings bound and 5/6 unbound. Some felt, as Richard Bentley put it, that the cost reflected 'y^{e} honoure of y^{e} Book' – though it surely also resulted from the costs of including so many mathematical figures in a book that neither Halley nor Streater were certain would sell very well.[129] Yet despite this success, Newton substantially did not alter his cautious views of printing. The second edition, edited by Roger Cotes, did not appear until 1713.

While the Royal Society had been suspicious of collective authorship from the start, and ultimately relinquished their role as active publishers of scientific books for financial reasons, the Paris Academy upheld the ideal of collective research to a much greater degree in their early publications.[130] Initially the goal of the Paris Academy involved attracting the most promising naturalists, mathematicians and astronomers in Europe, foreign and French, into the service of Louis XIV. Such efforts allowed the Academy to lay claim to great works such as Huygen's *Horologium oscillatorium* (1673) and the comparative anatomist Claude Perrault's *Mémoires pour servir à l'histoire naturelle des animaux* (1671). Subsequently the Academy, under Colbert's direction, crafted publications that reflected their cooperative endeavours, giving glory to the French king rather than any one academician. Perrault (1613–88) himself observed that collective authorship eliminated those errors that arose from the imperfections of one mind.[131] Accordingly the second volume of the history of animals (1676) belonged to the academy rather than him. It appeared in the same year as the *Récueil de plusieurs traitez de mathématiques de l'Académie Royale des Sciences*, which listed individual authors by chapter, and the *Mémoires pour servir à l'histoire des plantes*, which announced: 'this book is the work of the Academy as a whole.'[132]

Behind this seemingly tranquil façade lurked many problems. Academicians struggled to control editorial projects such as the vast, unfinished history of plants that intermittantly occupied the Paris Academy from the 1660s through the 1690s. Manuscripts were stolen by thieves on the road to Paris. Bitter quarrels broke out when the editorial collective refused its imprimatur to those works by members deemed inappropriate to bear the Academy's name because they did not reflect its philosophical goals.[133] By 1688 this process had been officialized in academy statutes to prevent works from bearing its name without firmer editorial control. In the midst of all these internal quarrels, financial and

publishing difficulties further undermined the ideal of collective publishing. Left to the mercy of the royal printers, who answered only to Colbert and not to the academicians, books languished in the presses. By 1681, as the cost of illustrations for the expensive folio histories of animals and plants mounted, Colbert withdrew funding to put it to use in more urgent matters of state. Ironically, this was the same year that he finally persuaded Louis XIV to visit his academicians, where he proudly showed 'His Majesty the printed works of the Academy, and a part of those to be printed'.[134] The king especially admired the manuscript illustrations of his royal naturalists, even if he no longer cared to fund their publication.

By 1699, when members of the Paris Academy drew up a new set of regulations, they acknowledged the utter failure of their initial goal, citing (in article 20) 'too many difficulties in works pursued in common'. At that point, they had spent some 12,000 *livres* on the engravings for Joseph Pitton de Tournefort's *Élemens de botanique* (1694) and allowed Tournefort to reassemble the shambles of their collective botanical project in order to publish it under his own name (precisely the sort of plagiarism that Hooke always feared).[135] Scientific knowledge had been produced, but at what cost and for whose benefit?

What form should it take?

The answers to these questions lay more precisely in the realm of other publications which emerged from the new scientific societies. In 1686, the writer, philosopher, and later perpetual secretary of the Académie des Sciences, Bernard le Bovier de Fontenelle (1657–1757) published his immensely popular *Entretiens sur la pluralité des mondes* which enjoyed some 28 editions before his death. In this series of conversations between a charming natural philosopher and a curious Marquise, the two muse over the cosmos and the possibility of life on other planets. As they imagine hypothetical inhabitants of Jupiter, Fontenelle's natural philosopher offers his vision of how Jovians might go about announcing their discovery of the planet Earth:

> There'll be astronomers on Jupiter who, after taking great pains to construct excellent telescopes, and choosing the finest nights to observe, will finally discover in the heavens a tiny planet that they've never seen before. First the *Philosopher's Journal* of that country will speak of it; the people of Jupiter either never understand anything about it or do nothing but laugh at it. The philosophers, whose judgments are destroyed by this, decide to believe none of it, and there are only a few very reasonable people who are willing to consider it. They observe it again, they're convinced it isn't a fantasy; they even begin to suspect that it moves about the Sun. They find at the end of a thousand observations that this movement is one year long, and finally, thanks to all the pains the scholars have taken, they know on Jupiter that our Earth is a planet.[136]

Fontenelle's passage reveals a number of trends in late seventeenth-century natural philosophical practice. Most obviously, the Jovians' insistence on obser-

vation reflects the growing importance of experimental and observational science in the latter half of the century.

But Fontenelle points toward significant changes in scientific communication as well by musing that the Jovian astronomers might immediately publish their findings in the '*Philosopher's Journal* of that country'. Since the first scientific journals had appeared in England and France only three years earlier, their presence in Fontenelle's description suggests how quickly these journals became an important element of imagined scientific practice. Moreover, the alien astronomers' awareness of an audience that includes not only other scholars, but also 'the people of Jupiter' marks a notable shift in the sense of audience for scientific observations. As the century neared its end, authors began to present natural philosophy in new forms (including the journal article) that made it accessible to a more popular audience and contributed to the growing sense of science as a fashionable pursuit.[137]

Before the first journals were published in 1665, natural philosophers might have learned of others' discoveries in a number of ways. They read each other's books when they could get a copy, of course, but only a fraction of natural philosophical knowledge appeared in this form. This was due, in part, to the difficulties people such as Kepler had in publishing their books. Additionally, the amount of time required to complete publication made this was an inefficient way to distribute new observations and experimental results. As one seventeenth-century man of letters put it, books 'require both Time and Assistance, for their due Maturity'.[138]

But the variety of forms in which natural knowledge appeared cannot only be attributed to deficiencies in the book trade. In addition to the printed book, the natural philosopher still viewed manuscripts, personal interactions and letters as equally important forms for communicating knowledge.[139] Correspondence networks were particularly useful in facilitating communication among natural philosophers. In their letters, learned men and women discussed the latest books, how they might get them, and disseminated other types of scientific news. Marin Mersenne (1588–1648) in Paris and Samuel Hartlib (1600–62) in London are only the two outstanding examples of men whose letterboxes served as hubs of international scholarly networks throughout the seventeenth century.[140]

Oldenburg (1615–77) continued this tradition in his official role as second secretary to the Royal Society of London from 1660 until his death in 1677. His duties included informing the Society of the activities of foreign natural philosophers, and in return dispersing information about the Society's own work. He explained that, as the Secretary, he 'writes all letters abroad, and answers the returns made to them, entertaining a correspondence with at least fifty persons, employs a great deal of time, and makes much pains in satisfying Forreign demands about philosophical matters, disperseth far and neare, store of direction and inquiries for the Society's purpose and seems them recommended.'[141]

Oldenburg was a particularly good candidate for this job. Although he was only second secretary to the Society, he increasingly came to hold primary

responsibility for the official correspondence. His language skills and experience abroad were particularly impressive: originally from Bremen, he later travelled for a number of years in France and made important scientific contacts there. He was fluent in all of the major European languages, and was adept at the often labyrinthine Latin of the scientific writings of the day.[142] But despite his qualifications for managing this international news network, Oldenburg quickly found that he alone could not keep the republic of letters informed about the Royal Society's and individuals' scientific work. Such an issue had already been raised as early as 1661, when Robert Moray informed Huyghens, 'from time to time we shall print what passes among ourselves, at least everything that may be published'. In 1665 Oldenburg responded to this dilemma (and perhaps a desire to make a profit)[143] by starting a journal initially entitled *Philosophical Transactions: giving some Accompt of the present Undertakings, Studies and Labours of the Ingenious in many considerable parts of the World*. As Oldenburg explained in his introduction to the first edition of the journal, improved communication was at the heart of the enterprise: 'Whereas there is nothing more necessary for promoting the improvement of Philosophical Matters, than the communicating to such, as apply their Studies and Endeavours that way, such things as are discovered or put in practise by others; it is therefore though fit to employ the *Press* ... '[144]

The journal was issued almost every month (although plague, the Great Fire of London, and the Society's summer recess often interrupted publication), and contained short reports in English on a variety of topics from both Royal Society members and foreign scholars. The first volume included reports such as 'An Accompt of a very odd Monstrous Calf', 'Extract of a Letter written from Rome, concerning the late Comet, and a New one', followed by 'Extract of another Letter from Paris, containing some Reflections on the precedent Roman Letter', 'An Account of Mr. Hook's Micrographia', 'Some Observations and Experiments upon May-dew', and 'Of some Philosophical and Curious Books, that are shortly to come abroad'.[145] This wide-ranging content served to keep the scientific community informed about observational and experimental work as well as new books in a wide range of fields, from medicine, to astronomy and optics.

The journal's sources were as diverse as its subject matter. Oldenburg took some of his material from meetings of the Royal Society, but much of it came from correspondents writing outside of London. He received contributions from Poland, Transylvania, Portugal and the American colonies, as well as Paris, Rome and Germany. Oldenburg made an explicit plea for foreign contributions in his preface to the second volume in 1666: 'we may thence take occasion to invite all Ingenious Men, and such as consider the importance of Cementing Philosophical Spirits, and of assembling together Ingenuities, Observations, Experiments and Inventions, scattered up and down in the World.'[146] Oldenburg received scientific news from a diverse group of people as well as places:

gentlemen virtuosi, physicians, members of foreign scientific academies, and even one 'understanding & hardy Sea-man'.[147]

Oldenburg's *Philosophical Transactions* quickly became an indispensable repository of news from all over Europe about scientific research and books (though the emphasis was definitely on the former). On one level, however, the journal seems to have been merely a more public form of the correspondence that Mersenne and Hartlib had mastered earlier in the century. The lines of communication were those laid down much earlier by correspondence networks, as Oldenburg's introductions to many of the 'articles' illustrate. A typical report began, 'There came lately from Paris a Relation, concerning the Improvement of Optick Glasses, not long since attempted at Rome by Signor Giuseppe Campani, and by him discursed of, in a Book, Entitled, Ragguaglio di nuove Osservationi, lately printed in the said City, but not yet transmitted into these parts ... .'[148] Just as in learned letters before, journal articles announced the publication of books and spread word of their content long before the books themselves made it abroad.

It was a short step from the letter to the journal article. Even before the learned journal, letters were often public material, to be loaned, copied and read aloud to interested scholars, and even printed. When the French astronomer and member of the Paris Academy Adrien Auzout (1622–91) apologized to Oldenburg for printing one of his letters, for example, Auzout explained that he understood letters to be public material:

> I am very sorry that you are displeased at my having printed (at the request of my friends) the letter you kindly wrote to me setting forth the opinions of Mr. Hooke. I did not regard this letter as being altogether your own work so much as the reply of Mr. Hooke and since both of us had already begun by printing this material I saw no inconvenience in printing the rest if our friends wished to see the sequel of the dispute. For I see little difference between printing scientific matters contained in letters and showing these same letters to those learned in these matters who can copy them out when they have them on loan ...[149]

Despite Oldenburg's objections, Auzout's decision to print his letter was quite normal. Given that learned correspondence often was so public already, the journal, in one sense, simply formalized and improved an existing communications structure.[150]

Although the *Philosophical Transactions* and other journals which followed were in some ways a continuation of the tradition of scholarly letters, they quickly served new functions. Because of the *Philosophical Transactions'* association with the Royal Society for example, it became an integral part of the Society's larger project of a collaborative, Baconian investigation of nature.[151] This project sought to eschew philosophical and theological aspects of science and focus instead on collecting 'matters of fact' about nature. These bits of information, gathered by observation and experiment, were to form the base of a new science, unbiased and unencumbered by theology and philosophy.[152] Oldenburg himself was fully committed to this new approach to the investiga-

tion of nature. His association with his patron Boyle, one of the leading advocates of the Baconian method, convinced him of the importance of this project and he continued to work towards its realization through his involvement with the Royal Society and the *Philosophical Transactions*.

Communication among scholars took on new importance with the advent of Baconianism. As Oldenburg was well aware, the kind of international collaborative project that Boyle and his Royal Society colleagues had in mind necessitated collaboration. An ideal of open communication would allow scientists to coordinate their findings and, eventually, build a new philosophy of nature based on their research. 'You will please to remember,' Oldenburg wrote, 'that we have taken to taske the whole Universe, and that we were obliged to doe so by the nature of our dessein. It will therefore be requisite, that we purchase and entertain a commerce in all parts of ye world wth the most philosophicall and curious persons, to be found every where.'[153] The *Philosophical Transactions* was to be the centre of this communication; as its editor, Oldenburg took on the role of 'an almost universal orchestrator of scientific inquiry'.[154] He often put virtuosi in touch who were working on similar projects, and even at times fostered debate by encouraging his correspondents to respond to one another and printing their reports together in the *Philosophical Transactions*.[155]

Oldenburg also played an important role in defining the new science by only selectively responding to correspondents' letters, often ignoring their philosophical or theological aspects. When Philip Jacob Sachs, for example, asked, 'Is it possible to revivify crabs by Digby's method?' Oldenburg dismissed the question, explaining that it had to do with 'causes, and these we have hitherto refrained from determining, in part to matters of fact'.[156] Oldenburg mobilized his ideas about what was proper material for the new science in choosing material for the journal as well. Although seventeenth-century science still consisted of a wide range of themes and approaches, material that diverged from the Baconian ideal largely did not appear in the *Philosophical Transactions*. This selectivity also came from contributors themselves. Boyle, for example, contributed numerous articles to the journal on his experiments with the air-pump; yet he chose not to contribute any of his alchemical experiments.[157] Increasingly, whether material was selected by Oldenburg or his correspondents, the *Philosophical Transactions* defined the new science by only presenting a particular type of knowledge.

It was important that the journal be not only selective but also authoritative if collaborative work was to take place. If contributors and readers were to make use of the accounts of other colleagues (often unknown to them personally), they needed to be able to trust their contents. The *Philosophical Transactions* quickly came to be seen as a trustworthy forum for the exchange of knowledge by drawing its authority from the Royal Society. It also made the claim that the knowledge submitted to its pages was only to be used for the unbiased investigation of nature. Oldenburg reminded his readers and potential contributors of the journal's standards in his preface to the second volume in March, 1666:

> I hope, our Ingenious Correspondents have examin'd all circumstances of their communicated Relations, with all the care and diligence necessary to be used in such Collections; not taking up old Fame, or flying Reports, upon too easie trust; nor straining for other Kinds of Wonders, than the most wise Author of Nature hath allowed, but attending closely to the strict measures of *Natural Truth*, and to the useful Contrivances of *Art*.[158]

The journal, in other words, expected its correspondents' sources to be reliable and their intentions to be free from personal or ideological bias.

Because of the *Philosophical Transactions*' importance in both drawing the lines of the new science and providing a space for the exchange of ideas that was both trustworthy and authoritative, it has received a great deal of attention from historians of science. The importance of the journal was also recognized at the time, and Oldenburg received numerous requests to produce translations of the journal into Latin, French, or Italian. Jean Denis, for example, wrote to Oldenburg in 1668 lamenting, 'I have often wished that instead of the copies in English which you send to France, you would send just one in French. I would gladly have had it printed at my expense both for your own reputation and the gratification of an infinite number of the inquisitive, who be delighted to be able to read and understand them by themselves, instead of which there are only three or four who see them.'[159] Eventually, the first volumes of the journal were translated into Latin from 1665 to 1681, and into French, German and Italian in the eighteenth century. Abstracts from the journal were also published in most other major European languages throughout the late seventeenth and eighteenth centuries.

The *Philosophical Transactions* became a model for one type of scientific periodical, and it was quickly joined by a number of other journals with similar purpose. In 1670, for example, the German Collegium Naturae Curiosorum in Schweinfurt resolved to issue the *Miscellanea Curiosa Medico-Physica* as a forum for the work of its members. In 1673, the *Acta Medica et Philosophica Hafniensia* appeared in Copenhagen in connection with the Danish Academy. It consisted largely of short reports on original medical or natural philosophical subjects.[160] Like the *Philosophical Transactions,* these journals all served mainly to inform an international scientific community of the research activities of their society's members and provide a forum for the exchange of information.

Scientific journalism at the end of the seventeenth century was as diverse as science itself, however, and it would be short-sighted to direct all of one's attention to the *Philosophical Transactions* and its emulators. Alongside this initiative arose another type of journal, equally important, but which served a different purpose. This other genre was initiated by the French *Journal des Sçavans*, founded by Denis De Sallo in 1665 and loosely associated with the Paris Academy. The *Journal des Sçavans* was followed somewhat later by the German *Acta eruditorum* (1682) and the Italian *Giornale dei Letterati* (1696).[161] Rather than modelling themselves on the *Philosophical Transactions* and focusing on experimental and observational reports, these journals consisted for the most part of reviews of literary and scientific books.

It might be tempting to dismiss the importance of this type of journal for the history of science, for as the French virtuoso Henri Justel wrote to Oldenburg, the editors of the *Journal des Sçavans* 'are rather historians than philosophers; that is why you see nothing in it dealing with physics. Perhaps in time they will add to it.' Oldenburg confirmed this opinion in a letter to Boyle: 'I find what is Philosophicall, to be taken out of our Transactions; ye rest being, generally, Extracts and Abbreviats of Theologicall, Historico-Politicall and such like Books.'[162] Despite their less scientific emphasis, however, the *Journal des Sçavans* and other book review journals served a substantial need in the republic of letters by informing its members about an increasingly voluminous and dispersed book trade.

The German philosopher and statesman Gottfried Wilhelm Leibniz's (1646–1716) efforts to start a book review journal reveal some of the conditions that necessitated these guides to the book market. In 1668, he petitioned the Emperor Leopold I for an imperial privilege for a journal to be entitled *Nucleus librarius semestralius*. Modelled in part on the French *Journal des Sçavans*, the *Nucleus* was to appear twice a year, coinciding with the book fair in Leipzig. It was to be organized around the four faculties, and contain short summaries in Latin of the books that were to appear at the fair. Leibniz's aim was in part to clarify some of the confusion in the German book trade, for as he saw it, the situation in the 1680s was so disorganized that 'one hardly knows anymore what one needs in such a crowd, and where one should look for it'.[163] The *Nucleus* would serve as a guide to the vast array of books on the market, and allow the potential buyer to make informed decisions.

Leibniz's plan for the *Nucleus* encompassed the international reader as well who might not be able to travel to the Leipzig book fair. He explained that, 'he who has neither the means nor the opportunity to buy books, or because of distance [is unable] to get them or see them, can nevertheless have sufficient material through this summary [in the *Nucleus*] to understand [the book] on his own and to discuss from it.'[164] Thus, Leibniz hoped, the *Nucleus* could also help restore the cosmopolitanism of the German book trade by ensuring that even those with no access to the Leipzig book fair could still be aware of the books for sale there. In the face of the dissolution of the book market into innumerable localized and vernacular printing centres, Leibniz's plan (though it never came to fruition) sought to prevent at least some of this decentralization.[165]

Not everyone agreed on the good of these book reviews. Adrien Baillet, for example, felt that reviews encouraged laziness and superficiality. 'Many people love & seek out these Abridgements,' he wrote, 'because they are appropriate to laziness, because they want to skim over the surface of things, & because they consider themselves skillful when they know the general definitions, the divisions & the terms of the Arts. But judicious persons believe rightly that it is better to be entirely ignorant of things than to know them badly.'[166] The Bishop of Soissons, Pierre-Daniel Huet, took a more apocalyptic view: 'When in Rome people made Abridgements of the great Latin works, & at Constantinople of the

great Greek works, barbary followed close behind.'[167] Despite the objections of Baillet and others who shared his opinions, however, the book review quickly assumed an important place in learned communities. Without them, it might have been impossible to keep track of the burgeoning traffic in scientific books.

Part of the scholar's problem in keeping abreast of either scientific reports and experiments or scientific books in foreign countries was the fact that authors and journalists were relying increasingly on vernacular languages rather than the international Latin. Oldenburg commented to Boyle in 1665 that Italians 'love every whit as well to read books in Italian, as ye English doe to read ym in English', and even preferred the vernacular if it was available.[168] Scholars' own preferences for their vernacular complemented their growing desire to appeal to a public for science that may not be schooled in Latin or willing to wade though thick tomes of natural philosophy. Oldenburg, for example, explained in 1669 that he deliberately had chosen to publish the *Philosophical Transactions* in English, despite foreigners' pleas for translations, 'because they are intended to be for the benefit of the such Englishmen as are drawn to curious things, yet perhaps do not know Latin'.[169]

The virtuosi's increased use of the vernacular demonstrates their desire to address their knowledge of nature to a broad audience. The new format of the journal article contributed to natural philosophy's growing accessibility as well. Physically the journal was cheaper and much easier to obtain and circulate than large and costly books. In addition, the short reports of 'matters of fact' allowed readers easily to follow the announcement of new discoveries. They did not require the deep philosophical, humanist or theological background of earlier natural philosophical writings. Finally, the Baconian focus on utilitarian science attracted new consumers of science because it emphasized its immediacy to their lives.[170] In all of these ways, the journal appealed to and helped create a new audience for a new science.

But the journal was not the only source of the popularization of science. Authors like Fontenelle deliberately reached out to new audiences by creating an entirely new genre of natural philosophical knowledge. In his *Entretiens* Fontenelle used the series of conversations between his philosopher and the Marquise to explain Copernican and Cartesian cosmologies. The reader could follow the philosopher's witty and fanciful ruminations as he gradually seduced the Marquise into the new science, creating a work that Fontenelle compared to such pleasurable genres as the novel, the opera and the play. His work quickly became one of the most popular books of its day. Furthermore, by making one of his conversationalists a woman, Fontenelle widened his audience even further, demonstrating that natural philosophy could be understood and appreciated by both sexes.[171]

Fontenelle's formula proved to be enormously successful, and the book went through over 15 editions in French alone in his lifetime. It has been translated since then into English, Danish, Dutch, German, Greek, Italian, Polish, Russian, Spanish and Swedish. In some ways, the success of the *Entretiens* was sympto-

matic of how popular science had already become by the late seventeenth century. Efforts tentatively begun by Kepler, pursued more enthusiastically by Galileo, Kircher and Boyle, and given new outlets in the journals began to bear fruit in the reception of Fontenelle's work. But Fontenelle has been rightly credited with generating a new demand for science as well. Through the *Entretiens*, and his role as secretary for the Paris Academy, Fontenelle consciously tried to present knowledge about the natural world in a form that non-experts could understand. By inviting women to participate in natural philosophy, he widened its audience even farther and paved the way for its inclusion in the salon culture of the eighteenth century. Fontenelle also demonstrated that science could be entertaining, if not seductive. In so doing, he created a new place for natural knowledge in elite social circles, outside the universities and academies, and in a sense gave it a new social function. Science, he showed his readers, could be fashionable.

Fontenelle stands out for his efforts in the seventeenth century, but by the eighteenth century, popularized accounts of natural philosophical discoveries were abundant. Elites increasingly consumed natural philosophy and 'matters of fact' in journals, in conversation, in demonstrations, and of course, in books. By the end of the century, the new forms for knowledge had generated new audiences for science. They had also helped reorganize the community of natural philosophers in the wake of the intellectual revolutions of the sixteenth and seventeenth centuries. Natural philosophers of the seventeenth century had used print creatively to recreate science and take it in rewarding new directions.

The author in the marketplace

When Leibniz reflected on the book trade in 1700, he lamented its state in the Holy Roman Empire. Printers and scholars, who had once worked so closely together, had increasingly less contact, thus, in his opinion, diminishing the quality of books produced. The commercialization of the book trade reinforced this tendency, Leibniz argued, as the hope of profit supplanted the more noble goal of disseminating knowledge in guiding the choices made by publishers and booksellers. He denounced this 'great abuse in the world of books, in which the booksellers often see only their profit, and do not turn themselves to that, which supports the common social body, but rather publish false, pernicious and vexsome writings ... '.[172]

Trends in the market only reinforced Leibniz's perception of booksellers' base greed by ensuring that profits could be found more readily in the local vernacular market than in the former international book trade. With the collapse of the Frankfurt book fair in the 1680s and 1690s, the German market lost the geographic centrality that placed it the crossroads of the European book trade. When the fair moved to Leipzig, it lost its international focus as it turned inward and became far more provincial.[173] Booksellers and publishers grew

much less willing to take risks on scholarly books for an international audience as their international clientele shrunk, preferring instead to produce and sell popular works in German that brought in a high profit and served the local market. The situation in the German lands mirrored that in Europe as a whole: the largely centralized, international (Latinate) book trade of the sixteenth century was slowly disintegrating into numerous small, vernacular and localized centres for the production and sale of books. This trend, for Leibniz, signalled a decline of knowledge itself in the German lands, 'the bread of the soul', for he viewed books as essential to the preservation and transmission of learning. If booksellers and publishers were no longer willing to print and sell scholarly works, he believed, learning would soon be lost.[174]

Leibniz's condemnation of the book trade in the German lands stemmed from his first-hand experiences as both a consumer and producer of books. He served the dukes of Hannover and Wolfenbüttel throughout the 1670–80s as librarian, and was responsible for acquiring books and manuscripts for their collections.[175] He assisted the Leipzig professor Mencke with the journal *Acta eruditorum* in the 1680s and 1690s by writing reviews of new books, particularly in mathematics and natural philosophy. As a natural philosopher in his own right, Leibniz regularly contributed his own articles to the *Acta eruditorum* concerning geometry, differential calculus, mechanics and metaphysics, and published several other books on jurisprudence, physics and optics.[176] Like any seventeenth-century scholar, Leibniz also bought books for his own use. Like Kepler, Leibniz was familiar with nearly every aspect of print culture.

Leibniz's plan in 1668–69 for the *Nucleus librarius semestralis* illustrates his early thinking on the book trade. He not only wished to guide buyers through the vast array of books for sale, but also hoped that informed buyers would be more interested in scholarly literature. Faced with customers asking for the quality books that his journal would review, Leibniz hoped, booksellers might be encouraged to carry more than the usual popular literature. Leibniz felt that there was a discernible gap in the market between educated buyers' desire for high quality books and booksellers' willingness to stock only books that they believed were the most profitable: popular, vernacular writings.[177] The *Nucleus*, he hoped, would help reunite authors, readers and sellers.

This early opinion was no doubt only reinforced by Leibniz's attempt to market his own (self-published) collection of common-law documents, the *Codex juris gentium* (1693). From the beginning, Leibniz was well aware of the need to market the book carefully. He convinced his friend Mencke, editor of the *Acta eruditorum*, to print an announcement of the forthcoming book in November 1692. He submitted similar announcements in February 1693 to the Leipzig *Monatlichen Unterredungen*, and the Rotterdam *Histoire des ouvrages des sçavans*, and continued to drum up interest by circulating the title page of the *Codex* with a summary printed on the reverse. This advertising campaign appeared to have worked quite well, and Leibniz soon received letters from Frankfurt and Paris eagerly anticipating the publication of the book.

When Leibniz actually tried to sell the *Codex* to booksellers, however, he was bitterly disappointed. His printer travelled to the book fair in Leipzig, and Leibniz tried to arrange sales contracts through various contacts in Holland, Lyons, London, and Florence. Ultimately, however, he had little luck. Booksellers were either uninterested, unwilling to take on the cost and inconvenience of international transportation, or they imposed special conditions (such as barter) that Leibniz refused to meet. In the end, despite an obvious demand by scholars, Leibniz found that booksellers were unwilling to take a gamble on a scholarly book.[178]

Leibniz made it his life's work to find a solution to what he perceived as the tyranny of base booksellers over learned authors and readers. The journal, in his view, was one solution. Although he failed to win support for the establishment of the *Nucleus*, he continued to provide learned readers with information about forthcoming books in the *Acta eruditorum*. He also saw a second path of reform in the intervention of the state through book commissions and learned societies. The two went hand in hand for Leibniz: state-sponsored learned societies would cultivate learning and increase the demand for high quality books, while book commissions would regulate the quality of the book trade from the supply side. It was in the state's best interest, he argued, to support the pursuit of knowledge which it could use to serve its own economic and political interests.

Leibniz got his chance in 1700 when Sofie Charlotte, future Queen of Prussia, extended an invitation to him to help establish the Berliner Sozietät der Wissenschaften. In Leibniz's vision, the promotion of learning and learned books were one and the same. His plans for the organization of the Society included important mechanisms to reform the book trade. Just as he had done 30 years earlier in Mainz, Leibniz encouraged the establishment of a book commission which would function as a censor to prevent the printing of harmful books, and encourage the publication of 'useful works and honest books'.[179] This, he hoped, would stop the flood of what he perceived as useless books. It would also place booksellers under the control of the Berlin Society and force them to submit to its standards. But perhaps more importantly, Leibniz argued, the Society should support the production of good literature by resolving to finance a certain number of publications and insure others against the risk of the market. The ideal way to reduce this risk, he claimed, was subscription publishing, whereby orders for the book were taken before its publication. With these measures, Leibniz hoped that the Society could resolve some of the tensions between the scholar and the market by mediating between them.[180]

Leibniz had been proposing similar measures for decades, and overall, he had about as much success convincing his patrons to fund these projects as Kepler had with his. Many of the issues Leibniz was concerned with had occupied Kepler as well at the beginning of the century. It was still difficult to finance publication, and many authors, like Leibniz, still had to finance their own books. Finding booksellers willing to distribute books was also problematic, and authors had to rely on personal contacts as much at the end of the century

as they had at the beginning. Overall, Leibniz's experience might give the impression that print culture had changed little over the course of the seventeenth century.

What had changed, however, were the resources scientific authors had to mitigate these tensions. They could (and did) use the journals to navigate the book trade and to generate interest in their forthcoming publications. This, in some ways, allowed them to manipulate the rules of the market in their own interest. Authors had a new institutional base, the scientific society, that supported their publication either by providing printers, regulating the book trade to defend learned books, or by actually funding publishing projects themselves. They had a new variety of forms to choose from in publicizing their work as well: the learned book, the journal article and, increasingly, more popular forms such as Fontenelle's *Entretiens*. Finally, the widening audience for the investigation of nature and its increasing vogue both as a topic of conversation and of reading gave it a new vitality as well. All of these factors gave scientific authors at the end of the seventeenth century a flexibility in doing business in the marketplace that they previously did not have.

The organization and institutionalization of science, innovations in communication, and its popularization are well-established themes in the history of science in the seventeenth century. Viewed from the perspective of the history of print, these innovations seem to have a new importance, for in addition to all the other reasons for their significance, they also provided the author with new solutions to the problems inherent in seventeenth-century print culture. As Leibniz's reflections on the book trade illustrate, these milestones in the history of science were in part a response to the tensions and difficulties of print and generated out of them. For the seventeenth century, print lay at the heart of the study of nature, and the history of science in this period cannot be fully understood without it.

Notes

1. Kepler, Johannes (1984), *Apologia pro Tychone contra Ursum* (written in 1600), in Jardine, Nicholas *The Birth of the History and Philosophy of Science: Kepler's A Defense of Tycho against Ursus*, Cambridge, UK: Cambridge University Press, p. 181.
2. Bacon, Francis (1960), *Novum Organum*, ed. Fulton Anderson, New York: Macmillan, p. 118 (Aphorism 129).
3. Lowood, Henry E. and Rider, Robin (1994), 'Literary technology and typographic culture: the instrument of print in early modern science', *Perspectives on Science*, 2, 8–15. See also Thoren, Victor E. (1990), *The Lord of Uraniborg: A Biography of Tycho Brahe*, Cambridge, UK: Cambridge University Press, *passim.*
4. Biblioteca Universitaria, Bologna, *Aldrovandi*. The broader context of Aldrovandi's publishing efforts is discussed in Findlen, Paula (1994), *Possessing Nature: Museums, Collecting, and Scientific Culture in Early Modern Italy*, Berkeley: University of California Press, pp. 346–92.

5. Biblioteca Ambrosiana, Milan, G. 188 (233), f.2 33r (Aldrovandi to Federico Borromeo, Bologna, 17 February 1601).
6. 'So unbridled is the ambition of some that when the booksellers refuse their writings, they spend large sums to publish and advertise themselves, thus imitating Ulysses Aldrovandus , who squandered his entire patrimony upon an edition of his own writings, free copies of which he placed in all the public libraries as monuments to his generosity and wisdom.' Mencke, Johann Burckhard (1937), *The Charlatanry of the Learned (De charlataneria eruditorum, 1715)*, trans. Francis E. Litz and ed. H. L. Mencken, New York: Knopf, pp. 71–72.
7. Gesner had published few of his works upon his death in 1565. When Mercati died unexpectedly in 1593, his catalogue to the Vatican mineralogical collection, the *Metallotheca*, remained in manuscript form, unpublished until 1717. For more on the transformation of this sixteenth-century manuscript into an eighteenth-century book, see Cooper, Alix (1995), 'The museum and the book: the *Metallotheca* and the history of an encyclopaedic natural history in early modern Italy', *Journal of the History of Collections*, 7, 1–24.
8. Findlen, *Possessing Nature*, pp. 24–28.
9. The sale of Aldrovandi's books is recorded in the Archivio di Stato, Bologna, *Assunteria di Studio. Diversorum*, t. 10, n. 6 (item 3); on Hooke's purchase, see Rostenberg, Leona (1989), *The Library of Robert Hooke: The Scientific Book Trade of Restoration England*, Santa Monica, CA: Modoc Press, p. 80. Hooke also owned the English translation of Naudé.
10. Fulco, Giorgio (1986), 'Per il "museo" dei fratelli Della Porta', in *Il Rinascimento meridionale. Raccolta di studi pubblicata in onore di Mario Santoro*, Naples: Società Editrice Napoletana, p. 8. Ultimately, since della Porta never accepted this agreement, no publication occurred. For the remarkable publishing history of della Porta's *Natural Magic* (1558), which enjoyed numerous editions through the seventeenth century, see Eamon, William (1994), *Science and the Secrets of Nature*, Princeton: Princeton University Press, pp. 194–233.
11. This episode will be discussed later in the essay.
12. *The Correspondence of Henry Oldenburg*, ed. A. Rupert Hall and Marie Boas Hall, Madison: University of Wisconsin Press, 1969, VI, pp. 91–93. Also cited in Lowood and Rider, 'Literary technology,' p. 26, n. 48. An important exception to this trend were the popular and often anonymous 'books of secrets,' whose publication history is treated extensively in Eamon, *Science and the Secrets of Nature*.
13. Eisenstein, Elizabeth (1979), *The Printing Press as an Agent of Change*, Cambridge, UK: Cambridge University Press, p. 18. Eisenstein discusses the impact of printing on science in 'Part Three: The Book of Nature Transformed', pp. 451–708.
14. In Jardine, *The Birth of the History and Philosophy of Science*, pp. 277–78.
15. See Eisenstein, (1992), *Printing Press*; and Anthony Grafton, *New Worlds, Ancient Texts*, Cambridge, MA: The Belknap Press of Harvard University Press.
16. For biographical information on Kepler, see Caspar, Max (1948), *Johannes Kepler*, Stuttgart: W. Kohlkammer; and Koestler, Arthur (1960), *The Watershed: a Biography of Johannes Kepler*, Latham, MD: University Press of America.
17. Anthony Grafton has done the most to bring to life Kepler as a humanist and a reader. See his 'Humanism and science in Rudolfine Prague', in *Defenders of the Text: The Traditions of Scholarship in an Age of Science, 1450–1800*, Cambridge, MA: Harvard University Press, 1991, and idem (1992), 'Kepler as a Reader', *Journal of the History of Ideas*, 53, 561–72.
18. Sethus Calvisius to Kepler in Prague, Leipzig, mid-1609, in Max Caspar and

Walther von Dyck, (eds), *Johannes Keplers Gesammelte Werke* [hereafter cited as *GW*] (Munich: C. H. Beck, 1937), vol. 18, #531.
19. See Koestler, *Watershed*, p. 72.
20. Caspar, *Johannes Kepler*, p. 72.
21. Kepler to Christoph Besold, November, 1627, *GW*, vol. 18, #1063.
22. Galileo to Kepler, August 4, 1597. In Koestler, *Watershed*, p. 175.
23. Ibid., p. 237.
24. See Caspar, *Johannes Kepler*, pp. 369–91.
25. Kepler to Georg Brahe, April, 1627, *GW*, vol. 18, #1043.
26. Wilhelm Schickard to Lukas Schickard, July, 1626, *GW*, vol. 18, #1115.
27. For this point, see Ashworth, William (1991), 'The Habsburg Circle,' in Bruce Moran, ed., *Patronage and Institutions: Science, Technology and Medicine at the European Court, 1500–1750*, Rochester, New York: The Boydell Press, p. 141.
28. *Doctor Fludds Answer unto M. Foster or The Squeesing of Parson Fosters Sponge* (1631), as cited in J. B. Craven, *Doctor Robert Fludd*, [n.p.]: Occult Research Press, [n.d.], p. 63.
29. On Fludd and his debates with Kepler, see Alan Debus, *The English Paracelsians*, New York: Franklin Watts, 1966, esp. pp. 105–27.
30. Caspar, *Johannes Kepler*, p. 159; and Koestler, *Watershed*, p. 161.
31. Much of this material is drawn from Owen Gingerich's (1971) insightful study of this frontispiece in 'Johannes Kepler and the Rudolfine Tables', *Sky and Telescope*, 30, 328–33 and Jardine, *Birth*, pp. 287–89.
32. Jardine, *Birth*, pp. 287–89.
33. Caspar, *Johannes Kepler*, pp. 280–81.
34. On Fludd's illustrations, see Joscelyn Godwin, *Robert Fludd: Hermetic Philosopher and Serveyor of Two Worlds*, London: Phanes Press, 1991.
35. On the De Bry family, see Sondheim, Moritz (1933), 'Die de Bry, Matthäus Merian und Wilhelm Fitzer', *Philobiblon*, 6, 8–34, Weil, E. (1944), 'Wilhelm Fitzer, the Publisher of Harvey's *De Motu Cordis*, 1628', *The Library*, 4th series, 24, 142–64, and Frances Yates, *The Rosicrucian Enlightenment* (London: Ark Paperbacks, 1986), pp. 70–90.
36. Anatomical books were a second type of book which, in addition to occult works, tended to use illustrations. On Harvey's publication with the De Brys, see Weil, 'Wilhelm Fitzer'. For a more complete bibliography, see Geoffrey L. Keynes, *A Bibliography of the Writings of William Harvey 1578–1657*, 2nd edn (Cambridge, 1957); French, Roger (1994), *William Harvey's Natural Philosophy*, Cambridge, UK: Cambridge University Press and Frank, Jr., Robert G. (1980), *Harvey and the Oxford Physiologists*, Berkeley: University of California Press.
37. Yates has made the strongest case for this argument in *Rosicrucian Enlightenment*, pp. 70–90.
38. Kepler to Philip Mueller, October 27, 1629. In Koestler, *Watershed*, p. 246.
39. Kepler in Sagan to Gerhard von Taxis in Gitschin, October 10, 1629, *GW*, vol. 18, #1115.
40. See Lowood and Rider, 'Literary technology'.
41. This anecdote is recounted in Favaro, Antonio (ed.) (1937), *Le Opere di Galileo Galilei. Ristampa della Edizione Nazionale*, Florence: G. Barbèra, XVIII, p. 172 (hereafter GO). Liceti is one of the less well-known but prolific Latin authors of the seventeenth century, whose works issued not only from printers near the University of Padua but also from small operations such as that of Nicolai Schiratti in Udine, who published his *Litheosphorus, sive De lapide Bononiensi*, Udine, 1640.
42. The collecting of scientific books is a large subject that can only be treated sporadically in this essay. For an introduction to this subject, see especially Wells,

Ellen B. (1983), 'Scientists' libraries: a handlist of printed sources', *Annals of Science*, 40, 317–89. Studies of early modern scientific libraries not cited elsewhere in the footnotes include: Canone, Eugenio (1991), 'Il *Catalogus Librorum* di Isaac Boeckman', *Nouvelles de la Republique des Lettres*, 1, 131–59; Feisenberger, H.A., 'The libraries of Newton, Hooke, and Boyle,' *Notes and Records of the Royal Society of London* 21 (1966), 42–55; Forbes, Eric G. 'The library of the Rev. John Flamsteed, F.R.S.', *Notes and Records of the Royal Society* 28 (1973), 119–43; Harrison, John R. and Laslett, Peter, *The Library of John Locke* (Oxford: Oxford Bibliographical Society, 1965); Prandtl, Wilhelm, *Die Bibliothek des Tycho Brahe* (Vienna, 1933); Sherman, William, *John Dee: The Politics of Reading and Writing in the English Renaissance* (Amherst: University of Massachusetts, 1995); and Wilkinson, Ronald Sterne, 'The alchemical library of John Winthrop Jr. (1606–1676) and his descendants in colonial America,' *Ambix* 11 (1965), 33–51 and 13 (1966), 139–86.

43. See Kepler, *Somnium* (1634) and Bacon, *New Atlantis* (written 1624; published 1627). Yet another popular tradition that already existed in the vernacular in the sixteenth century but grew in popularity in the seventeenth century concerned astrology. For a discussion of these printed materials, see Capp, Bernard, *Astrology and the Popular Press: English Almanacs 1500–1800*, London: Faber, 1979; and Patrick Curry, *Prophecy and Power: Astrology in Early Modern England*, Princeton: Princeton University Press, 1989.
44. Drake, *Discoveries*, p. 62 (original in GO, X, p. 351, Galileo to Belisario Vinta, Padua, 7 May 1610). This passage is also discussed in Eisenstein, *Printing Press*, p. 681, n. 130; and Eamon, 'Court, academy, and printing house: patronage and scientific careers in late Renaissance Italy', in Moran (ed.), *Patronage and Institutions*, p. 47.
45. See the *Dialogo di Cecco di Ronchitti*, Padua, 1605.
46. Galilei, Galileo, *Operations of the Geometric and Military Compass*, trans. Stillman Drake, Washington, DC: Smithsonian Institution Library, 1978, p. 36. Also discussed in Lowood and Rider, 'Literary technology', p. 36.
47. Galileo, *Operations*, p. 41.
48. GO, X, pp. 280, 297, 300.
49. Ibid., X, p. 300. The publication of this work is discussed extensively in Galileo Galilei, *Sidereus Nuncius or The Sidereal Messenger*, ed. and trans. Van Helden, Albert, (1989), Chicago: University of Chicago Press, esp. pp. 17–34. I have drawn extensively on this work in my discussion.
50. GO, X, pp. 374, 384. The subject of Galileo's patronage and the role of publication in this system has been studied in great detail in Biagioli, Mario (1993), *Galileo, Courtier: The Practice of Science in an Age of Absolutism*, Chicago: University of Chicago Press.
51. The role of books in the making of Galileo's career is also discussed briefly in Johns, Adrian (1998), *The Nature of the Book: The Making of Knowledge and the Cultures of the Book in Early Modern England*, Chicago: University of Chicago Press, ch. 1. This work is surely the most important point of departure for any scholar interested in the intersections between the history of science and the history of the book.
52. GO, XI, pp. 304, 333–34.
53. Ibid., p. 12. Gabrieli, G., 'La prima biblioteca lincea o libreria di Federico Cesi', *Rendiconti della R. Accademia Nazionale dei Lincei. Classe di scienze morali, storiche e filologiche*, (1938), ser. 6, 14, 606–28; Antonio Favaro, (1886), 'La libreria di Galileo Galilei', *Bulletino di bibliografia e di storia delle scienze matematiche e fisiche*, 19, 219–93; and de Renzi, Silvia, 'Contributi per una ricostruzione della biblioteca privata di Cassiano dal Pozzo', and 'La biblioteca di

Johann Faber Linceo', both in *Bibliothecae selectae. Da Cusano a Leopardi*, ed. Eugenio Canone, Florence: Olschki, 1993, pp. 139–70, 517–24.

54. On Aldrovandi and the Linceans, see Findlen, *Possessing Nature*, pp. 75–76; on Bacon, see de Renzi, 'Contributi', p. 142. Dal Pozzo acquired three of Bacon's works during a trip to Paris in 1625, since they were not readily available in Italy.
55. GO, XI, p. 422.
56. GO, XI, pp. 409, 423, 438. A great deal of information about the publishing of this work is also provided in Drake, Stillman, 1978, *Galileo at Work*, Chicago: University of Chicago Press, pp. 184–209.
57. GO, XI, pp. 459–60.
58. This subject will be discussed in greater detail in a forthcoming edition and translation of the sunspot debate by Mario Biagioli and Albert Van Helden.
59. GO, XI, p. 484.
60. Ibid., p. 494.
61. Ibid., p. 125. Due to slow sales, the *Istoria e dimostrazioni* did not enjoy a Latin edition in Rome, as Galileo hoped. As Stelluti wrote at the beginning of 1615: 'Before reprinting them in Latin, it will be necessary to wait a little longer in order to send these forward; otherwise it won't serve any purpose.'
62. Ibid., p. 332. On the Ambrosian Library, see Angelo Paredi, *Storia dell'Ambrosiana*, Milan: Neri Pozza, 1981.
63. GO, XVIII, p. 352.
64. Capecchi, Anna Maria, et al., (1992), *L'Accademia dei Lincei e la cultura europea nel XVII secolo*, Rome: Accademia Nazionale dei Lincei, pp. 105–6. Stigliola also published the important *Dell'historia naturale* (1599) of the Neapolitan apothecary Ferrante Imperato.
65. Campanella, Tommaso (1994), *A Defense of Galileo*, trans. Richard J. Blackwell, Notre Dame: University of Notre Dame Press, pp. 37–38 (Adami, 'Greetings to the Benevolent Reader from the Publisher'). Infelise, Mario, 'La censure dans le pays méditerranéens, 1600–1750', in *Commercium Litterarium: Forms of Communication in the Republic of Letters, 1600–1750*, ed. Hans Bot and Françoise Waquet, Amsterdam: APA-Holland University Press, 1994, pp. 276–77. The banning of Kepler's *Epitome* in 1620, for instance, certainly increased its circulation in Italy according to contemporaries; see Langford, Jerome J., *Galileo, Science and the Church*, rev. edn, Ann Arbor: University of Michigan, 1971, p. 104.
66. This episode and its publications are discussed in detail in Pietro Redondi, *Galileo Heretic*, trans. Raymond Rosenthal, Princeton: Princeton University Press, 1987, pp. 28–67. Translations of all these texts appear in Stillman Drake and Charles D. O'Malley, (eds), *The Controversy on the Comets of 1618*, Philadelphia: University of Pennsylvania Press, 1960. This episode is discussed well in Biagioli, *Galileo Courtier*, pp. 245–311.
67. GO, XIII, p. 134. Also quoted in Redondi, *Galileo Heretic*, figure 1 (between pp. 150–51). Grassi published under the pseudonym 'Lothario Sarsi' in this debate.
68. GO, XIII, pp. 141–42.
69. Ibid., pp. 148, 376.
70. Ibid., pp. 148, 155. The final editing was entrusted to the poet Tommaso Stiglioni in April and May; Redondi, *Galileo Heretic*, p. 46, n. 44.
71. In Fantoli, Annibale (1994), *Galileo for Copernicanism and for the Church*, trans. George V. Coyne, S. J., Notre Dame: University of Notre Dame Press and Vatican Observatory Foundation, p. 294, n. 59.
72. GO, XIV, p. 160; on the problems of printing, see also Fantoli, *Galileo*, pp. 311–17; Drake, *Galileo*, p. 313. For a more complete history of this book, see Richard S. Westfall, 'Patronage and the publication of the *Dialogue*', in his *Essays on the*

Trial of Galileo, Notre Dame: University of Notre Dame Press and Vatican Observatory Publications, 1989, pp. 58–83.

73. GO, XIV, pp. 324, 351. The timing makes the Jesuit mathematician Bonaventura Cavalieri's query to Galileo on 31 August 1632 all the more understandable: he had sent 50 copies of one of his books to Landini in exchange for 40 of Galileo's and wondered why they had not arrived; GO, XIV, p. 378.
74. Key documents surrounding the condemnation of Galileo's work can be found in Maurice Finocchiaro (ed.), *The Galileo Affair: A Documentary History*, Berkeley: University of California Press, 1989.
75. Westman, Robert S. (1984), 'The reception of Galileo's *Dialogue*: A Partial World Census of Extant Copies', in *Novità celesti e crisi del sapere*, Florence: Giunti Barbèra, p. 334. This argument also lies at the core of Biagioli, *Galileo Courtier*, though he does not discuss the content and physical circulation of the *Dialogue* in the same detail as Westman.
76. GO, XIV, pp. 356–57. This letter is also translated in Westman, 'Reception', p. 374.
77. GO, XV, p. 26. For a slightly different translation, see Finocchiaro, *The Galileo Affair*, p. 226.
78. Finocchiaro, *The Galileo Affair*, p. 260. Needless to say, the extant documentation is more ambiguous than Galileo's claim to have multiple offers since it indicates primarily how undecided Galileo was about where to publish and how difficult it was to find the right personnel to complete the printing and deal with the poor communications between different European states occasioned by the plague of 1630.
79. GO, XVI, p. 101. Translation in Westman, 'Reception', p. 338.
80. GO, XVI, pp. 258, 288, 298, 415. See also Westman, 'Reception', pp. 338–39. For more on the press that subsequently published most of Galileo's works between 1635 and his death in 1642, see David W. Davies, *The World of the Elseviers 1580–1712*, The Hague: Martinus Nijhoff, 1954.
81. Davies, *World of the Elseviers*, pp. 58–63, 97, 103.
82. GO, XVI, p. 448. The publishing history of the *Discorsi* is also summarized well in Drake, *Galileo at Work*, pp. 365–97, *passim*.
83. Ibid., XVI, pp. 326–27, 453, 455. Ian Maclean discusses the importance of new material for licensing editions of previously published material in his 'The market for scholarly books', p. 23.
84. For a brief discussion of Elzevier's role in publishing the 'new' philosophy of the seventeenth century, see Davies, *The World of the Elseviers*, p. 105. This included such works as Descartes' *Discours de la méthode*, Leiden, 1637, *Principia philosophiae*, Amsterdam, 1644, and the Latin edition of the *Geometria*, 1649.
85. GO, XVII, p. 76.
86. Ibid., XVIII, p. 204. We know that the 50 copies of the *Discorsi* sent to Rome sold almost immediately; Fantoli, *Galileo*, p. 465.
87. GO, XVIII, p. 110.
88. Galileo, *Dialogue Concerning Two New Sciences*, xvii. The dedication was written on 6 March 1638. In it, Galileo presents himself as unaware of the Elzevier publishing projects, writing: 'I was notified by the Elzeviers that they had these works of mine in press...' (xviii).
89. GO, XVI, p. 481. This visit occurred in September 1636.
90. GO, XVIII, p. 348.
91. Fantoli, *Galileo*, p. 471. See Antonio Favaro, *Bibliografia Galileiana (1568–1895)* (Rome, 1896) for further references to the publication of Galileo's works.
92. In Middleton, W.E. Knowles (1971), *The Experimenters: A Study of the Accademia*

del Cimento, Baltimore: Johns Hopkins University Press, p. 72. This was probably a comment made by the principal editor Lorenzo Magalotti.

93. Baldini, Ugo (1992), '*Uniformitas et soliditas doctrinae.* Le censure *librorum* e *opinionum*', in his *Legem impone subactis. Studi su filosofia e scienza dei gesuiti in Italia 1540–1632*, Rome: Bulzoni, pp. 75–119. See also Houston, R.A., *Literacy in Early Modern Europe: Culture and Education 1500–1800*, London: Longman, 1988, pp. 161, 166.
94. On Kircher, see Godwin, Joscelyn, *Athanasius Kircher: A Renaissance Man and the Quest for Lost Knowledge*, London: Thames and Hudson, 1979 for general bibliography; Findlen, *Possessing Nature.* A more complete bibliography of the intellectual work on Kircher can be found in Findlen, 'The Janus Faces of Science in the Seventeenth Century: Athanasius Kircher and Isaac Newton', in Osler, Margaret (ed.) (forthcoming), *Canonical Imperatives: Rethinking the Scientific Revolution.*
95. Space does not permit a detailed study of this important form of publication. See Baldini, *Legem impone subactis*; Peter Dear, *Discipline and Experience: The Mathematical Way in the Scientific Revolution*, Chicago: University of Chicago Press, 1995; and Rivka Feldhay, *Galileo and the Church: Political Inquisition or Critical Dialogue?*, Cambridge, UK: Cambridge University Press, 1995.
96. Many of the details for this section are drawn from Fletcher John (1968), 'Athanasius Kircher and the distribution of his books', *The Library*, ser. 5, 23, 108–17; and Hein, Olaf, *Die Drucker und Verleger der Werke des Polyhistors Athanasius Kircher, S. J. Eine Untersuchung zur Produktionsgeschichte Enzyklopädischen Schrifttums im Zeitalter des Barock unter Berücksichtigung Wissenschafts- und Kulturhistorischer Aspekte*, Cologne: Böhlau Verlag, 1993.
97. These are, respectively: Petrucci, Gioseffo, *Prodomo apologetico alli studi chircheriani*, Amsterdam, 1677; de Sepi, Giorgio, *Romani Collegi Societatis Iesu Musaeum Celeberrimum*, Amsterdam, 1678; and Kestler, Johann, *Physiologia Kircheriana experimentalis*, Amsterdam, 1680.
98. In Fletcher, 'Athanasius Kircher', p. 116.
99. The second editions of the *Mundus subterraneus* appeared in 1678 and 1668. It was published in Dutch in 1682, following the translation of Kircher's *China illustrata* (1667) into Dutch (1668) and French (1670).
100. Rostenberg, *Library*, pp. 53, 72, 117.
101. Glauber, *Opera Omnia* (1651–56), 4 vols; expanded to 7 volumes in the Amsterdam 1661 edition. Van Helmont's *Opera Omnia* appeared posthumously in 1682. The majority of Van Helmont's treatises were published by his son Francis Mercury. Both philosophers had some of their works translated into vernacular languages such as English and French. The context of such work is elaborated well in books such as Pagel, Walter, *Joan Baptista Van Helmont: Reformer of Science and Medicine*, Cambridge, UK: Cambridge University Press, 1982; and Smith, Pamela H., *The Business of Alchemy: Science and Culture in the Holy Roman Empire*, Princeton: Princeton University Press, 1994.
102. Von Guericke also published his own account of these experiments: *Experimenta nova*, Amsterdam, 1672. Equally interesting is the work of another Kircher disciple, Francesco Lana Terzi, *Prodromo overo saggio di alcune inventioni nuovi*, Brescia, 1970.
103. More detailed information on early chemistry books can be found in Partington, J.R. (1961–70), *A History of Chemistry*, 4 vols, London: Macmillan, and Robert Multhauf, *The Origins of Chemistry*, New York: F. Watts, 1967.
104. Redi's letters and Cassini's broadsheets are discussed briefly in Brendan Dooley, 'The communications revolution in Italian science,' *History of Science* 33 (1995), 480.

105. Tribby, Jay, 'Cooking (with) Clio and Cleo: eloquence and experiment in seventeenth-century Florence,' *Journal of the History of Ideas* 52 (1991), 417–39; and Findlen, 'Controlling the experiment: rhetoric, court patronage and the experimental method of Francesco Redi,' *History of Science* 31 (1993), 35–64. See also Dino Praddi, *Bibliografia delle opere di Francesco Redi* (Reggio Emilia, 1941); and Ugo Viviani, *Vita, opere, iconografia, bibliografia ... di Francesco Redi* (Arezzo, 1924–31).
106. The first edition appeared as a partial zoology: *Animalia mexicana descriptionibus, scholissque exposita Thesauri rerum medicarum Novae Hispanae*, Rome, 1628. See Capecchi, *L'Accademia dei Lincei*, pp. 8–10, 13, 98.
107. Others included broadsheets such as the *Melissographia* (1625) and *Apiarum* (1625), both products of the Linceans' microscopic studies of bees; botanical works such as Fabio Colonna's *Minus cognitarum stirpium* (1616); and Francesco Stelluti's *Trattato del legno fossile minerale* (1637). All of these were published in Rome by Giacomo and Vitale Mascardi.
108. In Middleton, *Experimenters*, p. 73. The material in this section is drawn primarily from this study.
109. This issue is raised well in Biagioli, 'Etiquette, interdependence, and sociability in seventeenth-century science,' *Critical Inquiry* 22 (1996), 213–14.
110. Middleton, *Experimenters*, p. 77. The strength of the Roman printing industry relative to other parts of Italy is also mentioned in Jean-Michel Gardair, *Le 'Giornale de' Letterati' de Rome (1668–1681)* (Florence: Olschki, 1984), p. 26.
111. Middleton, *Experimenters*, pp. 76–77. The courtly uses of the *Saggi* are discussed briefly in Biagioli, 'Etiquette', pp. 213–14.
112. Early scientific periodicals are discussed in the next part of this essay.
113. Rivington, Charles A., 'Early printers to the Royal Society, 1662–1803', *Notes and Records of the Royal Society of London* 39 (1984), 1–2. See also Johns, *The Nature of the Book*; and idem (1991), 'History, science, and the history of the book: the making of natural philosophy in early modern England', *Publishing History*, 30, 5–30.
114. In Rivington, 'Early Printers', p. 9; and Rostenberg, *Library*, p. 16. Johns estimates that an average learned book sold 80–100 copies, with mathematical works selling even less. For more on these two figures, see Langdon Keynes, Geoffrey, *A Bibliography of Dr. Robert Hooke*, Oxford, 1960; and idem, *John Evelyn: A Study in Bibliophily with a Bibliographia of His Writings*, 2nd edn (Oxford, 1968).
115. Harwood, John T. (1989), 'Rhetoric and Graphics in *Micrographia*,' in *Robert Hooke: New Studies*, ed. Michael Hunter and Simon Schaffer, Woodbridge, UK: Boydell, pp. 119–47, quote on p. 130. On the peculiarities of Royal Society publishing, see Johns, *The Nature of the Book*; Biagioli, 'Etiquette', p. 226.
116. Johns, *The Nature of the Book*, ch. 6. The last three editions were printed by Martyn and Allestry.
117. In Eisenstein, *Printing Press*, p. 665. Both Oldenburg's and Malpighi's letters are invaluable resources for understanding seventeenth-century book production and distribution. See *The Correspondence of Henry Oldenburg*, ed. A. Rupert and Marie Boas Hall; and Howard Adelman, (ed.), *The Correspondence of Marcello Malpighi* 5 vols, Ithaca: Cornell University Press, 1975. For more on Malpighi's publications, see idem, *Marcello Malpighi and the Evolution of Embryology* 5 vols, Ithaca: Cornell University Press, 1966, and Carlo Frati, (1897), *Bibliografia Malpighiana*, Milan, repr. London, 1960.
118. In Hunter, Michael, *Establishing the New Science: The Experience of the Early Royal Society*, Woodbridge, UK: Boydell, 1989, p. 277. Like Hooke, Grew inher-

ited one of his projects, the museum catalogue from several predecessors in the Society.

119. In Ornstein, Martha (1913), *The Role of Scientific Societies in the Seventeenth Century*, New York: Columbia University Press, p. 154, n. 1. The details of the Willoughby fiasco are recounted in Hall, Marie Boas, *Promoting Experimental Learning: Experiment and the Royal Society 1660–1727*, Cambridge, UK: Cambridge University Press, 1991, pp. 106–7; and Johns, *Books of Nature*, ch. 6. On Ray, see Keynes, Geoffrey Langdon, *John Ray: A Bibliography*, Oxford, 1951, and Charles Raven, *John Ray, Naturalist: His Life and Works*, 2nd edn, Cambridge, UK: Cambridge University Press, 1950.
120. Harwood, John T. (1994), 'Science writing and writing science: Robert Boyle and rhetoric theory', in *Robert Boyle Reconsidered*, ed. Michael Hunter, Cambridge, UK: Cambridge University Press, p. 38. Boyle's success as an author has also been discussed in Johns, *Books of Nature*, ch. 6; and especially Steven Shapin, *A Social History of Truth: Science and Civility in Seventeenth Century England* (Chicago: University of Chicago Press, 1994). For a complete list of Boyle's works, see, Fulton, Farquhar John, *A Bibliography of the Honourable Robert Boyle*, 2nd edn, Oxford, 1961.
121. Johns, *The Nature of the Book*, ch. 6.
122. Idem, 'The idea of scientific collaboration: The "man of science" and the diffusion of knowledge,' in *Commercium Litterarium*, ed. Bots and Waquet, p. 17. One of Kircher's lists is reproduced in de Sepi, *Romani Collegi Societatis Iesu Musaeum Celeberrimum*, pp.61–66.
123. These episodes are discussed in Harwood, 'Science writing,' p. 40; and Johns, *Books of Nature*, ch. 6.
124. In Hall, A. Rupert, 'Newton and his editors', *Notes and Records of the Royal Society of London* 29 (1974–75), 29–52. Essential to any study of Newton's publications is Turnball, H.W., Scott, J.P., Hall, A. Rupert and Tilling, Laura (eds) (1959–77), *The Correspondence of Isaac Newton*, 7 vols, Cambridge, UK: Cambridge University Press.
125. Both of these quotations are from Westfall, Richard S., *Never at Rest: A Biography of Isaac Newton*, Cambridge, UK: Cambridge University Press, 1980, pp. 224, 246. In many respects, Newton exhibited affinities with fellow alchemical adepts such as Elias Ashmole who declined to name his sources in the *Theatrum Chemicum Britannicum* (1651) because they did not wish to be identified in print (ibid., p. 289).
126. Westfall, *Never at Rest*, p. 453; and Ornstein, *Role*, p. 159, n. 2. Given this fact, Halley's role in reviving the *Philosophical Transactions* as a form of publication for Society members had a certain degree of self-interest.
127. In Christianson, Gale E. (1984), *In the Presence of the Creator: Isaac Newton and His Times*, New York: Free Press, p. 286. I owe the anecdote about Joseph Streater to Adrian Johns' excellent research, *The Nature of the Book*, ch. 2.
128. *The Correspondence of Isaac Newton*, II, pp. 434, 437. This exchange is discussed well in Andrew Cunningham, 'How the *Principia* got its name; or, Taking natural philosophy seriously', *History of Science* 29 (1991), 377–92.
129. Christianson, *In the Presence of the Creator*, p. 313; Johns, *The Nature of the Book*, ch. 1 (Bentley quote).
130. The contrast between these two styles is highlighted especially in Biagioli, 'Etiquette', and Christian Licoppe, *La formation de la pratique scientifique. Le discours de l'expérience en France et en Angleterre (1630–1820)*, Paris: Éditions la Découverte, 1996.
131. Licoppe, 'The crystallization of a new narrative form in experimental reports (1660–1690)', *Science in Context* 7 (1994), 217. This discussion of the Paris

Academy is drawn primarily from Hahn, Roger, *The Anatomy of a Scientific Institution: The Paris Academy of Sciences, 1666–1803*, Berkeley: University of California Press, 1971, and Alice Stroup, *A Company of Scientists: Botany, Patronage, and Community at the Seventeenth-Century Parisian Royal Academy of Sciences*, Berkeley: University of California Press, 1990.

132. The latter work was edited by Denis Dodart. In Biagioli, 'Etiquette', p. 222, n. 97.
133. Stroup recounts an episode with Samuel Cottereau Duclos' Paracelsian and alchemical treatise *Dissertation sur les principes des mixtes naturels* (1680), which he published with Elzevier in Amsterdam instead; Stroup, *Company of Scientists*, pp. 87, 206.
134. In Licoppe, 'Crystallization', p. 226. The financial problems are discussed well in Stroup, *A Company of Scientists*, pp. 80, 207–8.
135. In Hahn, *Anatomy*, p. 30; and Stroup, *A Company of Scientists*, pp. 58, 113–15.
136. de Fontenelle, Bernard le Bovier (1990), *Conversations on the Plurality of Worlds*, trans. H. A. Hargreaves and ed. Nina Rattner Gelbart, Berkeley: University of California Press, p. 57.
137. Writes Adrian Johns: 'The experimental paper, the philosophical journal, the book review, the editor, and the critic were all new categories'. In his 'History, science, and the history of the book', p. 10.
138. Oldenburg's 'Epistle Dedicatory' to vol. 1 of the *Philosophical Transactions*, March 1665, p. 1.
139. Dooley, 'Communications Revolution', pp. 471–72.
140. On Mersenne, Hartlib and other correspondence networks, see Kronick, David A., *A History of Scientific and Technical Periodicals: The Origins and Development of the Scientific and Technological Press, 1665–1790* (New York: The Scarecrow Press, 1962), pp. 53–60. See also Goldgar, Ann, *Impolite Learning: Conduct and Community in the Republic of Letters, 1680–1750* (New Haven: Yale University Press, 1985).
141. In Kronick, *A History of Scientific and Technical Periodicals*, p. 57.
142. Hall, Marie Boas, 'Oldenburg and the art of scientific communication', *British Journal for the History of Science* 2 (1965), 283–84.
143. For Oldenburg's monetary motivations in starting the Philosophical Transactions, see Andrade, E. N da C., 'The birth and early days of the *Philosophical Transactions*', in *Notes and Records of the Royal Society of London* 20 (1965), 13–14.
144. In Harcourt Brown, *Scientific Organizations in Seventeenth-Century France (1620–1680)* (New York: Russell and Russell, 1934), p. 185; and Oldenburg, 'Introduction', *Philosophical Transactions*, vol. 1, no. 1, (March), 1665, 1.
145. *Philosophical Transactions*, vols 1–8 (1665).
146. Ibid., vol. 2 (1666), 414.
147. Ibid., vol. 1 (1665), 11.
148. Ibid., vol. 1, no. 1 (1665), 2.
149. Adrien Auzout to Henry Oldenburg, Paris, October 3, 1665. In *The Correspondence of Henry Oldenburg*, II, p. 518.
150. Kronick makes this argument in his *A History of Scientific and Technical Periodicals*.
151. On the Royal Society, see in particular Hunter, Michael, *Science and Society in Restoration England*, Cambridge, UK: Cambridge University Press, 1981.
152. For a concise summary of the Royal Society's Baconian program and Oldenburg's role in it, see John Henry, 'The origins of modern science: Henry Oldenburg's contribution', *British Journal of the History of Science* 21 (1988), 103–110.
153. Ibid., p. 104.

154. Hunter, 'Promoting the new science: Henry Oldenburg and the early Royal Society', *History of Science* 26 (1988), 166.
155. On Oldenburg's encouragement of controversy, see ibid., p. 170, and Hall, 'Oldenburg', pp. 286–7.
156. In Henry, 'Origins', p. 107.
157. Principe, L.M. (1992), 'Robert Boyle's alchemical secrecy: codes, ciphers and concealments', *Ambix* 30, 63–74.
158. *Philosophical Transactions*, vol. 2 (1666), 414.
159. In Kronick, (1990), 'Notes on the early *Philosophical Transactions*', *Libraries and Culture*, 25, 257. For a list of translations and abstracts, see pp. 260–64.
160. Kronick, *A History of Scientific and Technical Periodicals*, pp. 76–82.
161. Ibid., pp. 73–74; Gardair, *Giornale de' Letterati.*
162. Henri Justel to Oldenburg, c. Jan. 14, 1665/6, and Oldenburg to Boyle, March 6, 1665/6, in *The Correspondence of Henry Oldenburg*, III, pp. 12, 48–49.
163. As cited in Anna Stein-Karnbach, *G. W. Leibniz und der Buchhandel* (Frankfurt am Main: Büchhandler-Vereinigung GmbH, 1983), p. 1219. For more on Leibniz, see Emile Ravier, *Bibliographie des oeuvres de Leibniz* (Paris, 1937); and Paul Schrecker, 'Une bibliographie de Leibniz', *Revue philosophique* 63 (1938), 324–46.
164. In Stein-Karnbach, *G. W. Leibniz*, p. 1220.
165. The dissolution of the Frankfurt book fair in the 1680s and 1690s due to warfare and its move to Leipzig had serious consequences for the German book trade's international character. Leipzig was much less central than Frankfurt, and thus could not sustain Frankfurt's cosmopolitanism. See ibid., pp. 1204–14.
166. In Ann Goldgar, *Impolite Learning*, pp. 54–55. See more generally her discussion of journals, pp. 54–114.
167. Ibid., p. 54.
168. As cited in Hall, 'Oldenburg', p. 283.
169. Oldenburg to René François Sluse, 2 April 1669, as cited in Kronick, 'Notes', p. 254.
170. Rousseau, G.S. (1982), 'Science books and their readers in the eighteenth century,' in *Books and their Readers in Eighteenth-Century England*, ed. Isabel Rivers, Leicester: Leicester University Press, pp. 197–201.
171. See Nina Rattner Gelbart's introduction to Fontenelle's *Conversations*.
172. In Stein-Karnbach, *G.W. Leibniz*, p. 1346.
173. Ibid., pp. 1204–14.
174. Ibid., p. 1240.
175. On Leibniz's service to these Dukes, see ibid., pp. 1258–78.
176. On Leibniz's contributions to the *Acta eruditorum*, see ibid., p. 1269.
177. On Leibniz's plan for the *Nucleus*, see ibid., pp. 1217–27.
178. Ibid., pp. 1282–94.
179. Ibid., pp. 1228–36, 1346. Leibniz had encouraged his patron Prince Johann Philip von Schönborn of Mainz to erect a similar book commission in 1670.
180. Ibid., pp. 1345–54.

Chapter Six

Eighteenth-century Scientific Publishing

Brian J. Ford

The word 'scientist' was not in existence during the eighteenth century. This term, which was disliked by many (Faraday eschewed its use), did not appear in the literature until the mid-nineteenth century. 'We need very much a name to describe a cultivator of science. I should incline to call him a scientist', wrote William Whewell (1794–1866) in *The Philosophy of the Inductive Sciences from the Earliest to the Present Time*, (London, 1840). The scientist *de facto* had appeared some two centuries earlier. Robert Hooke (1635–1703) published his great work *Micrographia* in London during 1665, and with its wide-ranging discourse and its vivid portrayals of microscopic structures it can be seen as the first science book we would recognize in today's terms.

The eighteenth century falls in the crucial period between the foundation of science and the recognition of the scientist. Prior to the eighteenth century, science was grasping towards the light, circumscribed by uncertainty and unsure of its processes and prospects. By the end of the eighteenth century, scientific publishing was adopting a recognizably modern approach and many of the books of that period can stand confidently alongside the works taking us into a new millennium. The names of the eighteenth century are an impressive catalogue of brave endeavour and novel insights: John Ray and Edward Jenner, Gilbert White and Erasmus Darwin, Lazzaro Spallanzani and Georges-Louis, Comte de Buffon, Lavoisier and Franklin; indeed the strides taken in the life sciences in eighteenth-century Europe set the biological revolution on its way.[1] Their energies fuelled the Age of Enlightenment, and their heritage lives with us today.

There must have been over 100,000 publications in the field during that century. If we restrict ourselves to a single discipline, medicine, we can see from the published catalogues how extensive are the holdings. John B. Blake (1979), *A Short Title Catalogue of Eighteenth Century Printed Books in the National Library of Medicine*, Bethesda, Maryland, lists over 25,000 eighteenth-century titles. It is popular to imagine that little was originated in the United States at that time but one summary published in 1977, *Early American Medical Imprints, 1668–1820*, Arlington, Mass: Printers' Devil, contains over 2100 books, pamphlets, theses and broadsides. The *Catalogue of Printed Books in the Wellcome Historical Medical Library* gives further evidence. From volume II, the catalogue covers books printed from 1641–1850. Volume II (London, 1966) covers authors with initials A–E; it alone lists over 18,000 items. Volume III (1976) covers F–L, and Volume IV (1995) M–R. So far over 60,000 items have been listed, and the catalogue was not due to be completed prior to the new millennium.[2]

If a single catalogue for a disciplinary library collection consumes so much endeavour, it is clear that we cannot gain a detailed overview of the progress of the sciences through publication. Here I discuss some of the best-known authors and provide key examples of their *oeuvres*. Shorter summaries of other authors are offered, mostly as footnotes, and further examples are included of authors whom it is conventional to overlook, but whose work anticipated later developments. We shall begin with the oldest preoccupation of civilized mankind, the documentation of the living world (botany, zoology, and medicine), move to microscopy, turn then to chemistry, on to physics and astronomy, and finally to mathematics.

This was the era of the *ordering* of science, when the romance of a rational mind emerged, and the concept of quantification was suddenly to blossom.[3] One of the main thrusts of the eighteenth century was a move to classify and record all the splendours of nature. As the century dawned, a major opus of a great European naturalist was in the process of publication. John Ray (1627–1705) was born in Black Notley, a small village to the south of Braintree, Essex. The son of a blacksmith and a medicinal herbalist, the young Ray studied at Cambridge and graduated in 1648. For many years he remained at Trinity, teaching Greek, mathematics and humanities. Ray took holy orders in 1660, but during 1662 he was instructed to endorse a document supporting the Act of Uniformity and when (as a Puritan) he refused to sign he was obliged to quit his university position. He was supported financially by his young pupils and colleagues at Cambridge, most notably Francis Willughby (1635–72) with whom he toured Europe between 1663 and 1665. In 1672, Willughby tragically died and Ray remained at the family home, as tutor to the Willughby children, and was supported by a bequest from his deceased friend. Following his marriage to a young governess he was obliged to leave the household and in 1678 they returned to the village of his birth where he remained for the remainder of his life. He had helped lay the foundations of ecology in his book *The Wisdom of*

God Manifested in the Works of the Creation, published in 1691, in which he discussed the intereaction of species with their environment, and how their populations are controlled.

Many of Ray's other publications appeared during the seventeenth century, but his greatest work bridged the gap into the eighteenth. This was his masterwork *Historia generalis plantarum* published between 1686 and 1704. It is the first great work of scientific botany, and in it he describes 18,600 plant species in three volumes containing a total of 2996 folio pages. The modern sense of the term 'species' was originally defined in 1690[4] and John Ray was the first naturalist to popularize that term in his taxonomical endeavours. Ray's prodigious *opus* is remarkable for containing no illustrations. In this work he set out a classification of plants in an ordered taxonomic sequence. Little wonder he was later to be dubbed 'the English Aristotle'. One of Ray's greatest friends was Mark Catesby (1683–1749), a self-taught artist who drew birds against a naturalistic background. He travelled widely in Virginia, the Carolinas and Bahamas, and published an eleven-part *Natural history of Carolina, Florida and the Bahama islands* in 1731–43. Later editions were edited by his friend George Edwards (1694–1773). Edwards was born in Stratford, Essex, and as a young apprentice tradesman he travelled widely in northern Europe. He contributed many papers to the *Philosophical Transactions*, and published several important works on natural history. His *Natural history of birds [etc.]* was published in three parts between 1743 and 1750, and then translated into French. Edwards' great four-part *Natural history of uncommon birds, and some other rarer undescribed animals [etc.]* was published in 1743–51, with his *Gleanings of natural history* in three parts in 1758–64.

The eighteenth century was heralded by interest in the ordering and classification of plants. A pioneer, now often overlooked, was Joseph Pitton de Tournefort who was Professor of Botany at the Jardin Royal in Paris. He first published his *Élémens de botanique* in 1694. In it he catalogued 8846 vascular plants, illustrated with 500 copper-plate engravings. It emerged in English, considerably revised in translation, as *The compleat herbal* in two volumes dated 1719 and 1730. In it we read: 'The Italians eat the [tomato] as we do cucumbers, with pepper, oil and salt; some eat them boiled: but considering their great moisture and coldness, the nourishment they afford must be bad.' The system of classification proposed by de Tournefort was widely accepted at the time. Herman Boerhaave (1668–1738) studied divinity and natural philosophy in the Netherlands, and graduated in medicine at the University of Haderwijk in 1693. He published *Institutiones medicae* in 1708 and *Book of aphorisms* in 1709; in 1710 he published his *Index plantarum.* The next title, *Historia plantarum* (1727), was a selection of his botanical lectures compiled and edited by his associates. His pupils next produced *Institutiones et experimenta chemiae* (1724) based on his chemistry lectures. Boerhaave did not approve of the result, and produced a corrected volume under the title *Elementia chemiae* (1732). Boerhaave also saw several other works through the publication process. For example, he oversaw the publi-

4. Aldrovandi, *Ornithologiae* (1599).
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cation of Valliant's *Discours sur la structure des fleurs* (1718) at Leiden, and the same author's *Botanicon Parisiense* Amsterdam and Leiden, (1727).

Boerhaave assisted the father of modern taxonomy, Carl Linnaeus (1707–78), in his early work. Linnaeus dedicated his great work *Genera plantarum* (1737) to Boerhaave. He was born in Råshult, Sweden, one of two sons of Nils Linnaeus (1674–1748), a clergyman. The family name was coined from the Småland name for the linden tree, *Tilia microphylla*, 'linn', an ancient specimen of which grew on the family's property. The Swedish universities were greatly impoverished at the time, and the young Linnaeus went to Harderwijke in the Netherlands to gain his doctor's degree. He moved from there to Uppsala where, in 1730, he was appointed Lecturer in Botany. Linnaeus introduced a system of classification of plants based on the sexual organs, and adopted for everyday use a form of nomenclature in which organisms were distinguished by a single specific name. This, the binomial system of nomenclature, has since been adopted throughout biology. His first great book was the *Systema naturæ regnum vegetabile*, first published in 1735. The first edition contains only seven folio leaves, five of which are printed on both sides. In 1737 he published the first edition of the *Genera Plantarum*, and in 1753 the great *Species Plantarum*. The innovative first edition was published in facsimile in Berlin (1907) and Tokyo (1934). The Ray Society published a facsimile with a 176–page introduction by William Stearn (1957–59), and a further facsimile appeared at Nieuwkoop in 1964. A second, enlarged, edition appeared in Stockholm in 1762–63, and a corrected reprint (known as the 'third edition', though it has no other amendments) was published in Vienna. The move from lengthy descriptive Latin names towards a binomial system was promulgated by Linnaeus, originally as a means of economizing on paper. Many of the names he coined, indicated in zoology by the abbreviated suffix 'Linn.', and in botany by 'L.', are still widely used by new-millennium taxonomists.[5]

Others were quick to follow in documenting the natural world. The French naturalist Michel Adanson (1727–1806), born at Aix-en-Provence, visited the West African state of Senegal in 1749 and made extensive collections of specimens. His work was published as *Histoire naturelle du Sénégal [etc.]* (Paris, 1757) and later appeared in English as volume 16 of J. Pinkerton's *General collection of ... voyages [etc.]* (1814) London. Later he compiled an extensive two-volume work on taxonomy, *Familles des Plantes* (Paris, 1763, 1764). His library and papers are now at the Hunt Botanical Library, which has published a bicentennial commemoration of his taxonomic endeavours.[6] One of the pupils of Linnaeus was Carl Peter Thunberg (1743–1828), who left Sweden in 1770 to travel widely in Japan and Java, the Cape and Ceylon (now Sri Lanka), discovering some 1900 new species of plants. There are 293 publications in medicine and natural history to his name. Among the most notable are: *Sera uti Europa, Africa, Asia förätad ären 1770–79* (Uppsala, 1788–93); the *Flora Japonica* (Leipzig, 1784); *Prodromus plantarum Capensium [etc.]* (Uppsala, 1794–1800); and *Flora Capensis* (Uppsala, 1807).

Taxonomy was actively pursued by the English physician William Withering (1741–99). His father was an apothecary of Wellington, Shropshire. The young Withering studied medicine at Edinburgh where he graduated in 1766. He took up the post of physician at the Stafford Infirmary where he came to know Erasmus Darwin (1731–1802). The founder of the Lunar Society of Birmingham, William Small (1734–75) died suddenly and Darwin proposed that Withering take over Small's medical practice in Birmingham. This brought him into active participation in the Lunar Society, where he met many contemporary men of science including Matthew Boulton (1728–1809), James Watt (1736–1819), Josiah Wedgewood (1730–95) and Joseph Priestley (1733–1804). Withering published the now rare volume *An account of the foxglove, and some of its properties [etc.]* (1785) which established the value of *Digitalis purpurea* in the treatment of heart disease. Digitalin is still commercially obtained by extraction from a foxglove, *D. lanata*, to this day. Withering's greatest work was a version of the Linnaean system of classification, published as *A botanical arrangement of all the vegetables naturally growing in the British Isles [etc.]* (Birmingham, 1776) which ran through 14 editions, most published posthumously, with the last dated 1877. Withering also invented a low-power folding microscope in a wooden box, one of the most unsatisfactory designs of field microscope ever invented. It is figured in an engraving published in volume 1 of the *Botanical arrangement*. Withering also published *An Account of the Scarlet Fever and Sore Throat ... particularly as it appeared in Birmingham in 1778* (London, 1779). He was forced to leave Birmingham after expressing sympathy with the French Revolution (a similar fate befell Joseph Priestley) and he fled to Portugal during 1792–93. For many years he suffered from tuberculosis and withdrew from medicine to rest. In Portugal he published a little-known work *A chemical analysis of the water at Caldas da Rainha* (Lisbon, 1795). His archives are preserved at the Birmingham Central Library, along with papers of Boulton and other philosophers of the English Midlands.

Other systems of classification were proposed. In France a major project was undertaken by Bernard de Jussieu (1699–1777) and carried further by his nephew Antoine Laurent de Jussieu (1748–1836) who published many monographs on plant families. The young Jussieu published, as his major *opus,* the *Genera Plantarum* of 1789.[7] However, it was the Linnean system which triumphed, and which forms the basis of modern taxonomy. As the eighteenth century drew to a close, a luxurious work was published by Robert Thornton (1768–1837). Entitled *New illustration of the sexual system of Carolus Linnaeus*, it was published in parts between 1799 and 1807. The cost was more than Thornton could bear, and to help defray his expenses an Act of Parliament was passed to permit the holding of a national lottery for the benefit of the project. It failed to raise enough money, and Thornton was ruined by his extravagant publishing project.

In the laboratory, it was the physiology of the living plant which came to prominence during the eighteenth century. Stephen Hales (1677–1761) was born in Kent, and studied divinity at Cambridge for 13 years. Many of his

Cambridge studies which extended over animal anatomy, botany and chemistry were carried out in cooperation with his close friend William Stukeley (1687–1765). In 1709 he moved to Teddington on the Thames, where he remained as a minister for the rest of his life. He established a laboratory at home, and carried out innumerable experiments which served to advance the study of physiology. His paper *Vegetable staticks; or an account of some statical experiments on the sap in vegetables [etc.]* was read to the Royal Society in 1725, and published in 1727 as the first volume of his *Statical essays*, a book concerned with both plant and animal physiology. It is a small book illustrated with 20 detailed illustrations of his experimental methods. Hales, an inventor and pioneer of forced ventilation, also set plant physiology on a firm footing. He concluded, for example, that 'plants very probably draw through their leaves some part of their nourishment from the air'. Hales also showed that sap does not obtain its power to rise purely through root pressure. He concluded that the 'force is not from the roots only, but must proceed from some power in the stem and branches'. The book, for all its diminutive nature, became popular, and was translated into French by Buffon (*infra*) in 1735. The second part of the *Statical essays*, published as *Haemastaticks [etc.]* in 1733, translated into French by de Sauvages (1744). The two parts were jointly published in German (1748), Dutch (1750) and Italian (1750). Hales also published his *Philosophical experiments [etc.]* (1739) and later wrote an account of ventilation of prisons, *A description of ventilators and a treatise on ventilators* in two parts (1743, 1750). Physiological experimentation was carried further by Jan Ingenhousz (1730–99) of Breda, Netherlands. He was stimulated by the tide of investigation (including Priestley's discovery of oxygen, *q.v.*) and during the summer of 1779 carried out 500 experiments concerning the respiration of green plants. He discovered photosynthesis, and proved that – in the presence of sunlight – green plants take up carbon dioxide and release oxygen. Ingenhousz went further, and elegantly demonstrated that green plants, in the dark, respire like animals (consuming oxygen, and giving off carbon dioxide). His researches are described in the *Experiments upon vegetables, discovering their great power of purifying the common air in sunshine, but injuring it on the shade or at night* (London, 1779) and he followed it with *On the nutrition of plants* (1796). His collected writings, published as *Nouvelles experiences et observations sur divers objects de physique* (Paris, 1785) were dedicated to the great American experimenter, Benjamin Franklin.

In Denmark, Otto Friderich Müller (1730–84) edited a great work, *Flora Danica*, which had been founded by Georg Christian Oeder (1728–91). The work contained 3240 plates and was published in 54 volumes. The first appeared in 1761, but publication was not complete until 1883.[8] His first great book concerned zoological taxonomy. This, the *Zoologiae Danicae prodromus* (1776), was in some ways a prelude to the *Zoologia Danica*. The first volume of this impressive work appeared in 1777, volume 2 appearing in 1784. The final two volumes were published posthumously, edited and extended by an editorial

team headed by P.C. Abilgaard, in 1789 and 1806. Spanish botanical publishing in the eighteenth century was much advanced by the establishment of the Real Jardín Botánico at Madrid in 1755, and in the later decades by extensive collecting expeditions.[9] In Germany, the principles of pollination were investigated by Joseph Kölreuter (1733–1806) who published his researches in *Vorlaufige Nachricht von einigen des Geschlect der Pflanzen betreffenden Versuchen und Beobachtungen* (Leipzig, 1761). They were extended by Conrad Sprengel (1750–1816) in his *Das neu entdeckte Geheimnis der Natur im Bau und Befruchtung der Blumen*, published in 1793 and translated as *The discovered secret of nature in the structure and fertilization of flowers.* Sprengel revealed the role of the pollination process and showed how flowers were anatomically adapted to pollinating insects. It was a profound revelation, truly one of the great insights in botany, yet his book was widely ignored and he bitterly abandoned botany in favour of philology. One of Sprengel's sources of inspiration was Jean Jacques Rousseau (1712–78) whom we know as a philosopher, but who was an inspirational botanist as well. Born in Geneva, and unsuccessfully apprenticed to an engraver, he later earned his living as a music teacher until commissioned by Denis Diderot (1713–84) to write for his prodigious encyclopaedia. Rousseau was one of the most eloquent writers of the Age of Enlightenment. The age celebrated the use of the mind as a tool, and many of the greatest writers were active in the arts and the sciences, a flexibility to which few can aspire in the twentieth century but which reveals the majesty of human thought. Didérot, for example, published fact and fiction, essays and plays, art and literary criticism, in addition to his work as an encyclopaedist. He was commissioned in 1747 to edit a French translation of the *Cyclopaedia* by Ephraim Chambers. Initially in collaboration with Jean Le Rond d'Alembert (1717–83), a noted theoretical physicist and mathematician, he embarked on a grand project – a new and controversial 35-volume work, *Encyclopédie ou dictionnaire raisonné des sciences, des arts et des metiers*, generally known simply as the *Encyclopédie.* Many other celebrated writers contributed, including Voltaire and Montesquieu, and the work became a medium for propaganda against religiosity and feudalism. The Conseil du Roi actually banned the first 10 volumes published between 1751–59. The publication continued in secret, until 17 volumes of text were published by 1765, with plates and appendices added in 1780.[10]

Rousseau also wrote on the need for 'pure' botany with a modern insight: 'when we are used to looking at plants only as drugs or medicines ... one does not imagine that the structure of the plant is worthy of attention in itself'. His botanical papers were published 27 years after his death, as *La botanique de J.J. Rousseau* (Paris, 1805). The book is illustrated with 65 coloured plates, from original paintings by Pierre-Joseph Redouté (1759–1840) who, from his birthplace in the Ardennes region of Belgium, trained in Paris and became the *protégé* of Napoleon's wife Josephine. Many of the great works of botany in the early nineteenth century were illustrated by his vivid studies. Redouté's first published illustrations – some of them printed in colour – occur in the *Stirpes*

novae aut minus cognitae (1784–85) of Charles Louis l'Héritier de Brutelle (1746–1800). In Paris, meanwhile, d'Alembert published much work on his own. A landmark in mechanics was his *Traité de dynamique* (1743) which enunciated the concept of 'equal and opposite' forces. He applied the principle in the *Traité de l'équilibre et du mouvement des fluides* (1744). A sequence of publications ensued: *Réflexions sur la cause générale des vents* (1747); *Essai d'une nouvelle théorie sur la résistance des fluides* (1752); *Recherches sur différents points importants du système du monde*, three volumes (1754); and *Opuscules mathématiques* (1761–80).

In descriptive botany during the eighteenth century we may discern the supplanting of old techniques by more modern technologies. In 1755 H.L. Duhamel de Monceau published the last major work to be illustrated with old-fashioned woodcuts. This, the *Traité des arbres et des arbustes*, was a wide-ranging work but heralded the demise of the wood-cut block in botanical publishing. Twenty-five years earlier, Jacob van Huysum (c. 1687–1740) had published the first major botanical book with illustrations printed in full colour. This was the first volume of his planned *Catalogus plantarum* (1730) devoted entirely to trees. The engraved plates were inked with pigments of different colours *à la poupée* and each impression produced a full-colour illustration. It is interesting to note the first author ever to use this technique: Johann Teyler (1648–99) produced plates of plants inked up in this way in the closing years of the seventeenth century, but it was the van Huysum volume which pioneered the introduction of this technique to scientific publishing. As the century drew to its close, lithography was introduced by Alois Senefelder (1771–1874). His first successful lithographs appeared in 1797, though the first book containing plant illustrations printed lithographically was to be Rudolph Ackerman's *Series of thirty studies from nature* in 1812. Today's offset printing is directly descended from these early experiments of the eighteenth century.

One of the great stimuli to the taxonomy of plants was the new era of exploration. The first major voyage of exploration was under the command of James Cook (1728–79) who set out in the *Endeavour* in 1768. The voyage was conceived as a geographical and astronomical adventure, though Banks seems to have conceived of the potential for publishing of the natural history revelations even before they departed. On board the ship were Joseph Banks,[11] later President of the Royal Society, and Daniel Solander, student of Linnaeus. The artists on the *Endeavour's* voyages were Sydney Parkinson (a Quaker), William Hodges (son of a blacksmith) and John Webber (son of a Swiss sculptor). Much of their fine work was never published in their lifetimes. Parkinson's original studies are preserved at the Natural History Museum, London. The drawings by Hodges and Webber are preserved, largely unpublished, in collections. William Anderson (1748–78) accompanied Cook on two of his voyages and passed his extensive specimen collections to Joseph Banks. His journal exists in the collections of the Public Records Office.[12] Engravings from the original drawings by Sydney Parkinson were made during the 1770s but never published at the time.

The original engraved plates were recently found to be in excellent condition in the basement of the Natural History Museum, and have been published *à la poupée* for the first time during the 1990s by Editions Alecto.[13] Pulls of some of the plates (in black only) had been made during the eighteenth century, and there was a limited edition of 100 copies published as *Captain Cook's Florilegium* (London, 1973). However, the full collection of plates awaited publication in colour for 220 years, an unenviable record in scientific publishing. Parkinson died working overseas, and his *Journal of a voyage to the south seas* was published posthumously in 1773. The Department of Zoology of the Natural History Museum in London holds a book containing a further 40 water-colours by Parkinson, dated 1767, which were published in 1968 under the title *Forty drawings of fishes made by the artists who accompanied Captain James Cook on his three voyages round the Pacific 1768–71, 1771–75, 1776–80.* [See also: Sawyer, F.C. (1950). 'Some natural history drawings made during Captain Cook's first voyage round the world', *Journal of the Society for the Bibliography of Natural History*, 2 (vi), 190–193.]

Cook's first publication took the form of notes on a solar eclipse published in the Royal Society's *Philosophical Transactions* (1766). He published an account of the second voyage of the *Endeavour* in two volumes as *A voyage towards the South Pole, and round the world [etc.]* (1777). The account of the third voyage, co-authored with James King, appeared as *A voyage to the Pacific Ocean. Undertaken by command of His Majesty, for making discoveries [etc.]* in three volumes (London, 1784). The first two volumes were written by Cook, the third by King. The book sold out three days after its first publication, and was quickly reprinted. The third edition is dated 1785. Cook's account of his first journey is preserved in manuscript in the Mitchell Library, Sydney. It was published under the editorship of W.F.L. Wharton as *Captain Cook's journal during his first voyage round the world made in H.M. Bark 'Endeavour'* (London, 1893).[14] One of the natural philosophers who accompanied Cook on his second voyage was Georg Forster, who later travelled widely in Europe with Friedrich Heinrich Alexander von Humboldt (1769–1859) of Berlin. Baron von Humboldt made significant contributions to many of the sciences including geology and geophysics, meteorology and astronomy, botany and zoology. Inspired by Forster's accounts of the voyage with Cook, von Humboldt resigned his position as Inspector of Mines in Prussia in 1795 to devote himself to independent research and exploration. He published a regional botanical guide, *Flora Freiburgensis [etc.]* (1793) and a work in physiology *Versuche über die gereizte Muskel- und Nervenfaßer* (1797). As the century ended he departed on a 10,000 km (6,000 m) tour of South America, thus carrying into the nineteenth century a zeal for scientific exploration which was born in the eighteenth.

Not all notable botanical publishing was in the form of books. *The Botanical Magazine* was founded in 1787 by William Curtis (1746–99) and is published to this day. Curtis was born at Alton, Hampshire and moved to London to practice as an apothecary. In 1772 he was appointed *Praefectus horti* at the

5. Kepler, *Tabulae Rudolphinae* (1627).
Reproduced courtesy of Bernard Quaritch Ltd.

Society of Apothecaries' Garden in Chelsea and stayed in that position until 1777. He began publishing his *Flora Londoniensis* in May 1775, with further issues appearing at intervals until 1798. A two-volume edition appeared in 1777 and 1798. In the first edition there were over 400 plates, each hand-coloured, and this figure rose to almost 650 by the second edition. Three hundred copies of each were published, the plates being coloured by a team of 30 painters. He published 36 volumes of *English Botany* (1790–1814) containing a total of 2590 drawings.[15] The text for these books was in fact contributed by Sir James Edward Smith (1759–1828).

The best-remembered British naturalist of the time was Gilbert White (1720–93) of Selborne. His book, *The natural history and antiquities of Selborne*, has been through more than 200 editions and has been continuously in print since it first appeared. It was originally printed in 1789, the edition being published anonymously. The book contains letters on natural history, most of them written to his friends Thomas Pennant and Daines Barrington. White was educated at Oriel College, Oxford, but lived for most of his adult life in Selborne where he recorded innumerable observations on natural history. These were interspersed with personal observations in his diary. The year after his book was published, White wrote this entry in his journal: 'Mrs. Edmund White brought to bed of a boy, who has increased the number of my nephews and nieces to 56. One polyanth stalk produces 47 pips or blossoms'. White was an early proponent of the Linnean system of classification, evidence of his sound grasp of biological principles, and his writings exude an enthusiasm for the natural world.

We have seen that Rousseau, though better known as a philosopher, contributed to the advancement of science. Johann Wolfgang von Goethe (1749–1832) is perhaps most familiar as a poet and philosopher, but actively pursued interests in natural history and the sciences. His chief work in botany is *Versuch, die Metamorphose der Pflanzen zu erklaren* (1790) Gotha. It was reprinted in the same year, and was subsequently translated into French and English during the nineteenth century. His researches on the intermaxillary bone were published in 1784 (see Wells, G.A. (1967). 'Goethe and the intermaxillary bone', *British Journal for the History of Science*, 3, 348–61). He published a paper on colour theory, *Beiträge zur Optik* (1791), and wrote a paper on anatomy entitled *Erster Entwurf einer allgemeinen Einleitung in die vergleichende Anatomie* in 1795, though this was not formally published until it appeared in 1820 in *Zur Morphologie*. As the century ended he was working on the publication he regarded as his most important contribution to science. This was *Farbenlehre*, published in 1808.

Goethe's work was surrounded by controversy, and the repercussions of Lamarck's views were still apparent as the twentieth century drew to a close. Jean Baptise Pierre Antoine de Monet, Chevalier de Lamarck (1744–1829) was the eleventh child of an impoverished aristocratic family. He entered the army before choosing to devote himself to botany at the age of 24. In 1778 he published a great work in three volumes, *Flore Française*. A second edition was

published in 1793, and a third (edited by A.P. Candolle in six volumes) appeared in 1805–15. Lamarck was befriended by Buffon, the wealthy naturalist, and accompanied him on a tour through the Netherlands, Germany and Hungary. His interests turned towards geology, and he wrote *Hydrogéologie, ou recherches sur l'influence qu'ont les eaux sur la surface du globe terrestre [etc.]* in 1802. As the century turned, he was already showing a greater interest in zoology and it was this field which led him to propose views in the field of evolution which came to oppose those of Charles Darwin.[16] Darwin's theory had antecedents, as well as rivals. His grandfather Erasmus Darwin (1731–1800), born near Derby, qualified in medicine at Cambridge in 1755 and published a 'poem, in two parts, with philosophical notes'. This appeared as Part I: *The economy of vegetation* (London, 1791) and Part II: *The loves of the plants* (Litchfield, 1789); curiously, the second part appeared prior to the publication of the first. This work was later translated into French, Portuguese and Italian. He also wrote *Phytologia, or the philosophy of agriculture and gardening [etc.]* (1799),[17] and early in the next century appeared the posthumously published *Temple of nature [etc.]* (1803). Erasmus Darwin also wrote on zoology, curiously supporting the concept of spontaneous generation for a time. However, his two-volume *Zoonomia, or the laws of organic life* (London, 1794–96) was replete with advanced scientific ideas. It treats of pathology and generation, and sets out a concept of evolution which anticipates the theory later espoused by Alfred Russel Wallace (1823–1913) and expanded by Charles Darwin (1809–82).[18] A new edition of this seminal book was printed in London (1796) and as four volumes in 1801. It was printed as two volumes in New York (1796); a three-volume edition was printed in Philadelphia (1797), Dublin (1800) and Boston (1803). The American publications were reprinted during the early years of the nineteenth century.

Other notable writers of the period turned to the study of zoology from other areas of interest. Vicq d'Azyr (1748–94) was a physician in Paris who later specialized in comparative anatomy (notably of the brain). The only book published during his lifetime was *Traité d'anatomie et physiologie* (Paris, 1786), though his papers were collectively published in six volumes as *Oeuvres de Vicq d'Azyr, recueillées et publiées aves les notes et un discours sur la vie et ses ouvrages, par Jacq L Moreau* (Paris, 1805). A Berlin-born natural philosopher, Caspar Friedrich Wolff (1734–94) went to St Petersburg where he was elected to the Royal Academy of Science and specialized in embryology. His first major publication was *Theoria generationis* (Halle, 1759, reprinted in 1774), and was published in German as *Theorie von der Generationen* (Berlin, 1764). It has been reissued in more recent times – with an introduction by Robert Herrlinger- and republished in Hildesheim in 1966. One of Wolff's major books was initially published in a journal and did not appear in book form until the German translation was issued early in the nineteenth century.[19]

Edward Jenner (1749–1823) is renowned for his pioneering experiment on vaccination. The discovery was not the result of an individual insight, for

variolation (the use of serum from mild cases of smallpox) had been known for many years previously. The principles of variolation were first popularized in Britain by Lady Mary Montague (1689–1762) whose husband was British ambassador to Turkey. Vaccination, which utilizes an inoculation from a case of cowpox, rather than smallpox, had long been part of rural folklore. The fair face of the milkmaid resulted from her immunity to smallpox infection. On 14 May 1796, Jenner carried out his trials of inoculation with the cowpox virus, using an eight-year-old boy, James Phipps, as his experimental subject. Jenner was warned by the Royal Society not to injure his reputation further by associating himself with such superstitious traditions, and published the experiments privately in June 1798 as *An enquiry into the causes and effects of the variolae vaccinae, a disease by the name of cow pox*. This historic publication extends to a mere 75 quarto pages, with four coloured plates. A supplement appeared in 1799, *Further observations on the variolae vaccinae* and a *Continuation of facts and observations relative to the variolae vaccinae* and *A complete statement of facts and observations relative to the cow-pock* followed in 1780. These papers were all reprinted in the two-volume *Crookshank's pathology and history of vaccination* (1889).

Jenner was born in the Gloucestershire village of Berkeley where he spent most of his life. He became a pupil of John Hunter (*q.v.*) who used to write asking him to prosecute his enquiries into natural history and report back. Jenner's most celebrated early paper was 'Natural history of the cuckoo', published in *Philosophical Transactions* in 1788. It described the ejection of the young hedge-sparrow by the young cuckoo, and attracted considerable attention. Like his work on smallpox, this was not an original observation but was common knowledge among country people. The account does not stand up to scrutiny, for Jenner used his nephew Harry to make the observations and the indolent youngster, lacking the patience to make observations himself, wrote an imaginary account which Jenner offered as his paper for the Royal Society. It was later translated into French and Italian. Shortly after its publication in the *Philosophical Transactions* he was elected to the fellowship of the Royal Society.[20]

Other figures of the era had less orthodox careers. George Stubbs (1724–1806) produced fine studies of equine anatomy which have never been equalled. His father was a leather-dresser, and the young George trained as an engraver. He visited Italy in 1754, but for the next 20 years lived with his niece, Mary Spencer, in a remote Lincolnshire farmhouse. He suspended the body of a horse on a frame in his home, dissecting away the carcass in layers and painstakingly recording each structure as he found it. The odour of the decaying body spread for a considerable distance downwind of his home. Finding it impossible to employ an engraver willing to work on his project, he undertook to engrave each study himself. The final volume of 18 large folio tables and 23 plates was printed by J. Purser, for the author, in 1766. It was reprinted in 1853 and reissued by Bracken Press in 1990. It remains a peerless example of observa-

tional anatomy. Stubbs became a celebrated painter, claiming (without justification) to be a Royal Academician. A frequent subject was a lion attacking a horse, which stems from an episode Stubbs personally witnessed near Ceuta, North Africa, when on an excursion from his Italian sojourn. It made an indelible impression which lives on through his *oeuvres*. Four further volumes of Stubbs' work have been rediscovered among papers at the Free Public Library in Worcester, Mass. The work was entitled *A comparative anatomical exposition of a human body with that of a tiger and a common fowl*; Stubbs had started working on it in 1795, though he lived to see pulls from only a few of the plates. Extracts have since been published.

Francis Willughby (co-worker with John Ray) published a major book *Ornithology* in 1678. Among the budding naturalists it stimulated was the young Thomas Pennant (1726–98) who was given a copy at the age of twelve. Pennant was born in the Welsh county of Fflint, and matriculated at Queen's College, Oxford. He did not graduate but travelled extensively, and published a number of important zoological reference books, including *The British zoology* (1761–66), *Indian zoology* (1769 and 1790), *Genera of birds* (1773 and 1781), *Natural history of the turkey* (1781), and *Arctic zoology* (1784 and 1785). Curiously, he also wrote *The literary life of the late Thomas Pennant, Esq.* (London, 1793) which, in spite of the allusion in its title, was published five years prior to his demise.

An extraordinary work on tropical fish was published by Louis Renard (1678/9–1746). He lived a chequered life as a publisher and dealer in books, and for some years was an agent of the British Crown in the Netherlands. He served Queen Mary and the Kings George I and II, working against the interests of the exiled James Stuart and writing reports back to Britain. Little is known of Renard's background, and the only picture of him shows a distant figure smoking a long clay pipe as women file past in a brothel (Pietsch, note 21). His great work of natural history was *Poissons, Ecrevisses et Crabes* (Amsterdam, 1719) more popularly known as *Natural History of the Rarest Curiosities of the Seas of the Indies*. It is a notorious book, well known for the grotesque nature of the plates. They show absurdly coloured and distorted pictures of sea-creatures. As a work of scholarship, the book has been dismissed as 'crude' and 'barbarous' though its cartoons have made it a prized item among collectors of curiosities. However, some of the organisms have proved to bear a resemblance to existing species. Recent research has reconciled the published drawings with current zoological knowledge, and concludes that in only a few cases were the pictures entirely fanciful. This offers a new interpretation of the book: far from being a mass of fiction, it now seems to have been based on fact. The truth of the matter is that Renard could not draw.[21]

René Antoine Ferchault de Réamur (1683–1757), a native of La Rochelle, was for two centuries commemorated by the thermometric scale bearing his name. This, with the freezing-point of water at 0°R and boiling-point at 80°R, was still in use in parts of central Europe until the 1960s. Réamur studied

mathematics at Paris and published a method of smelting steel, but his greatest work was a book entitled *Mémoires pour servir a l'histoire des insectes*, published in Paris between 1734–42 in six volumes. It contained some 250 plates and over 5000 other illustrations. A seventh volume, uncompleted at the time of his death, was produced in Paris in 1928. Among his other works was an innovative treatise on the rearing of birds in incubators, *Art de faire éclore et d'élever en toutes saisons des oiseaux domestiques de toutes espèces*, originally published in two volumes in Paris dated 1749, with a second edition in 1751. It was translated into English by Abraham Trembley (*infra*) and was published in London in 1750 under the title *The art of hatching and bringing up domestic fowls, by means of artificial heat.* A German edition was published in 1767–68. Somewhat confusingly, a book on insects with the same title was published by Charles de Geer (1720–78), a native of Sweden. His own *Mémoires pour servir a l'histoire des insectes* appeared between 1752–78 in seven volumes and owed much to Réamur. It was also strongly influenced by the system of classification published by Linnaeus (q.v.). Réamur and Trembley jointly influenced the prolific work of Charles Bonnet (1720–93), a native of Geneva, Switzerland, born of French parents. Bonnet studied natural history extensively. He made studies of regeneration in the freshwater polype (named *Hydra* by Linnaeus in 1746) and the reproduction of aphids, and investigated insect respiration. His prodigious output gave rise to eighteen volumes entitled *Oeuvres d'histoire naturelle, et de philosophie* (Neuchâtel, 1779–83). The greatest work on *Hydra* was that done by Abraham Trembley (1710–84) of Geneva, while employed as tutor to the young children of Count Bentinck of The Hague. His book of 1744 is *Mémoirs, pour servir à l'histoire d'un genre de polypes d'eau douce, à bras en forme de cornes*, Leiden. It has been translated and published in an annotated volume as Lenhoff, S. G. and H. W. (1986) *Hydra and the birth of experimental biology*, California: Pacific Grove. The new edition, with its fold-out plates, is a fitting tribute to a detailed and painstaking programme of research, and the investigations have been set into context in Virginia Dawson's 1987 book *Nature's Enigma, the problem of the polype in the letters of Bonnet, Trembley, and Réamur* published in Philadelphia. Trembley's work was contemporaneously popularized in Britain by a bookseller and amateur enthusiast named Henry Baker (1698–1774) in his *A natural history of the polype* (1743) London. He also published *The microscope made easy [etc.]* (London, 1743), a book illustrated with many engravings derived from earlier authors, the second edition having an additional plate of a solar microscope. This had been invented by Leeuwenhoek, the design being perfected by J. N. Lieberkühn in 1739. Finally, there was Baker's 1753 book entitled *Employment for the microscope*, which further popularised the microscope in Britain. *Hydra* was also studied by August Johann Roesel von Rosenhof (1705–59) whose early writings appeared in a magazine entitled *Insekten-Belustigungen* and who in 1758 published a beautifully illustrated book *Die natürliche Historie der Frosche*, Nuremberg, on the natural history of frogs.

High-power microscopy had been born a hundred years earlier through the writings of Grew and Hooke, the latter inspiring the Dutch draper Leeuwenhoek to his great endeavours[22] as the founder of microbiology. Their work, which began in the seventeenth century, came to greater prominence in the eighteenth. Robert Hooke (1635–1703) died as the eighteenth century began, but the memorable images published in his great folio work *Micrographia* (first edition 1665, second edition 1667) continued in print. The first posthumous volume was *Micrographia restaurata* (London, 1745) printed for J. Bowles. It was followed by *Microscopic Observations, Dr Hooke's wonderful discoveries by the microscope [etc.]* (London: R. Wilkinson, 1780). Hooke's collected publications appeared in 1705 as a collection: *The posthumous works, including Cutlerian lectures, [etc.]*, published in London by R. Waller, S. Smith and B. Walford while in 1726 appeared the *Philosophical experiments and observations of R. Hooke [etc.]*, published by W. Derham, W. and J. Innys. All of Hooke's major papers were reprinted in Birch, T. (1756–57), *The History of the Royal Society of London*.

Antony van Leeuwenhoek (1632–1723), the draper of Delft, made many of his greatest discoveries during the seventeenth century. However, his works appeared in volume form predominantly during the eighteenth. Of the 20 editions in Dutch, 15 were published after 1695. The eighteenth-century books containing Leeuwenhoek's researches were: *Sevende Vervolg der Brieven, waar in gehandelt werd [etc.]* (Delft, 1702); *Vervolg der Brieven, gesschreven aan de Wytvermaarde Koninglijke Societiet in Londen* (3rd edition Leiden, 1704); *Ontledingen en Ontdekkingen van de Cinnaber naturalis [etc.]*, new edition (Leiden, 1713); *Send-brieven, zoo aan de Hoog-edele Heeren van de Koninklyke Societiet te Londen* (Delft, 1718); *Briefen Deel IV*, with portrait of Goeree (Delft, 1718); *Anatomia Seu interiora Rerum [etc.] editio novissima, prioribus emendatior* (Lugduni Batavorum, Boutestein, 1722); *Continuatio epistolarum* (third edition 1715, fourth edition 1730), Lugduni Batavorum (Boutestein); *Arcana naturae detecta* (third edition 1708, fourth *editio novissima* 1722, Lugduni Batavorum, Boutestein); *Continuato arcanorum naturae detectorum*, second edition (Leiden, 1722); *Epistolae ad Societem Regiam Anglicam [etc.]* (Lugduni Batavorum (Langerak), 1719),; *Epistolae physiologicae super compluribus naturae artcanis [etc.]* (1719) Lugduni Batavorum (Langerak); and the great *Opera Omnia, seu arcana naturae [etc.]*, four volumes (Lugduni Batavorum (Langerak), 1722). Fifteen letters addressed to Magliabechi were published by Targioni-Tozzetti in 1745 as *The Leeuwenhoek manuscripts in the National Library of Florence*, and an edited and censored version of many Leeuwenhoek letters was published by Hoole, S. (1798, 1807), *The select works of Antony van Leeuwenhoek, containing his miscroscopical* [sic] *discoveries in many of the works of nature*, two volumes, London. A second printing quickly followed, with the spelling corrected. Leeuwenhoek's illustrations were drawn to his instruction by a limner, and were used as a reference by later workers. For example, they appear in slightly altered form in Baker's work (*supra*).

6. Galileo, *Il Saggiatore* (1623).
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Leeuwenhoek's *Collected correspondence* is being published in an annotated English translation. The first volume was published in Amsterdam by Swets & Zeitlinger in 1939, and the twelfth volume appeared in 1989. This included letters dated 1696–99, halfway through Leeuwenhoek's 50-year career in microscopy. Thus the time taken by the translators to reach the mid-point of Leeuwenhoek's correspondence was slightly longer than the length of Leeuwenhoek's entire career.

Many illustrations of microscopes are to be found in a book by Louis Joblot (1645–1723) entitled *Descriptions et usages de plusiers nouveaux microscopes tant simple que composez [etc.]* 2 parts (Paris, 1718). This book is now rare. He followed it by *Observations d'histoire naturelle, faites avec le microscope [etc.]* two volumes (Paris, 1754–55). He was Professeur Royal en mathématiques de l'Académie Royale de peinture et sculpture in Paris. Many other authors published books on the microscopic animals found in nature.[23] The stimulus of an awareness of microscopical structure led to important research in several newly nascent areas. One of the first to appear was an opportunistic and fraudulent book written by an English quack, Mr Boil. It appeared as: Monsieur A. C. D. (1726), *Systême d'un medecin anglois sur la cause de touts les especes de maladies*, Paris, which illustrated a series of 91 curious creatures said to cause disease. It was disclosed in Vallisneri, A. (1733), *Opere fisico-mediche stampate e manoscritte ... raccolte de Antonio suo figliuolo*, Venice, that the book falsely claimed to be the work of a doctor trained in Persia. In fact, Mr Boil had a v-shaped instrument which allowed him to demonstrate small animals in a concealed tube to his patients while claiming to be focusing on their blood or urine.

More diligent and valuable investigations were carried out by Lazzaro Spallanzani (1729–99) of Scandiano. He carried out demonstrations to support a belief promulgated by Leeuwenhoek and substantiated by Francesco Redi (1626–97), namely, that spontaneous generation was a myth. Spallanzani studied law – his father's occupation – at Bologna, later embracing mathematics and French. At Reggio N'ellEmilia he was appointed Professor of Logic, Metaphysics and Greek and at Modena was Professor of Physics until 1769, when he became Professor of Natural History at Pavia where he died on 11 February 1799. Spallanzani's initial response to the spontaneous generation controversy is cited in the following section, but his other major findings were published as *Saggio di osservazione microscopiche relative al sistema della generazione* (Modena, 1767); *Prodromi suilla riproduzione animale [etc.]* (Modena, 1769); *De'fenomeni della circolazione [etc.]* (Modena, 1773); *Oppusculi di fisica animale e vegetabile [etc.]* (Venice, 1782); *Chimico esame [etc.]* (Modena, 1796); and *Mémoires sur la respiration [etc.]* (Geneva, 1803). There have been many editions, notably the six-volume *Le opere* (Milan, 1932–36) and the four-volume *Epistolaria* (Florence, 1958–59). Spontaneous generation had been advocated by John Turberville Needham (1713–81) and the Comte be Buffon (1707–88). Needham was a Roman Catholic Welshman who was much influenced by work

on infusion micro-organisms published in 1746 by 'Sir' John Hill (the knighthood was an invention). Hill, rightly dismissed as a 'quack', published in 1752 *Essays in natural history and philosophy: discoveries by the microscope*, London. During a short visit to Paris, Needham became acquainted with Buffon and took to his idea of spontaneous generation through the organization of 'organical parts' to fuel the *'prima stamina'* of life. Needham's work on this topic – which won him Fellowship of the Royal Society – was published in 1749 as 'A summary of some late observations upon the generation, composition, and decomposition of animal and vegetable substances', *Philosophical Transactions*, 490, 615. The ideas were translated and appeared as: *Nouvelles observations microscopiques, avec les découvertures intéressantes sur la composition et la décomposition des corps organisés* (Paris, 1750) and *Idée sommaire ou vue général du système physique et métaphysique de Monsieur Needham sur la génération des corps organisés* (Brussels, 1776).

The first major attack on this school of thought was published anonymously by the French metaphysician J. A. Lelarge de Lignac (1710–62) as *Lettres à un Ameriquain sur l'histoire naturalle générale et particulière de M. de Buffon*, which dismisses Buffon's work. Needham, when he saw it, said the work was being criticized 'avec une indécence et une arrogance si extraordinaire et avec si peu de connaisances que nous avons alors résolus ensemble de ne lui jamais répondre'. Voltaire, in *Des singularités de la nature* (1769) dismisses Needham as 'un jésuit irlandais [*sic*] nommé Needham qui voyageait dans l'Europe en habit séculier' and in *Histoire de Jenni* (1768) returns to the attack with remarks about 'un fou nommé Needham'. Spallanzani entered the fray with *Saggio di osservazioni microscopische concernenti it sistema della generazione dei Signori di Needham e Buffon* (Modena, 1765) which was translated into French by the Abbé Regley, who included many critical annotations by Needham. Spallanzani carried out a series of careful experiments which proved, beyond reasonable doubt, that micro-organisms were produced only from contaminated infusions. To counter Needham's unsubstantiated views he wrote an essay entitled '*Osservazioni e sperienze intorno agli animalucci delle infusioni* [etc.]' (Modena, 1776) in the celebrated *Opuscoli di fisica animale e vegetabile*.

Ideas of fermentation and infection crystallized during the nineteenth century, but the eighteenth gave them birth. The most influential eighteenth-century book on fermentation was Adam Fabbrioni's *Dell'arte di fare il vino*, published in Florence (1787) and translated into French by F. R. Baud in 1801. The author, otherwise unknown, is believed to be a brother of G. V. M. Fabbrioni (1752–1822). Pasteur recorded his belief that: 'Fabrioni peut donc être considéré à juste titre le principal promoteur des idées modernes sur la nature du ferment' [in: Pasteur, L. (1866), *Études sur le vin, ses maladies, causes et provoquent [etc.]*, Paris]. A remarkably prescient work on contagion was published by Benjamin Martin of London in 1720 (with a second edition in 1722). It was *A new theory of consumptions: more especially of a pthisis or consumption of the lungs*, a book apparently written for a popular audience. Martin, who lived in Theobald's Row,

found fault with the current theories: Dolaeus' volatile particles, van Helmont's ferments, Morton's 'ill-natur'd humours', Sylvius' salt acrimony, even Willis' sourness of the internal juice. Marten ascribed tuberculosis to:

> wonderfully minute living creatures that ... by their disagreeable parts are inimical to our nature but are however capable of existing in our juices and vessels and which, being drove to the lungs ... and by wounding or gnawing the tender vessels of the lungs cause all the disorders mentioned.

In this way he saw how animalcules could cause the 'deplorable symptoms of the disease', emphasizing how odd his theory must seem to those people who cannot imagine creatures 'besides [those] which are conscious to the bare eye [but are] infinitely smaller and wholly imperceptible to our eye though assisted by the best glasses'. This is an important, if speculative, book. Other writers were less inspired by far. Johannes Nyander in 1757 published *Resp. exanthemata viva [etc.]* at Uppsala, argued that the cheese and the itch mite were identical, and added that dysentery and smallpox, plague and syphilis, were all caused by mites. In 1762, Marcus Antonius Plenciz (1705–86) published *Opera medico-physica in quatuor tractatus digesta quorum primus contagii morborum [etc.]*, Vienna. In tract 1, section 1, he wrote of seeds of contagion which could be carried by the air and lie dormant, a view which sounds prophetic until later passages which show he believed these would eventually germinate to produce beetles, flies, leeches and gnats.

Pieter Lyonet (1706–89) was a Dutch lawyer whose made natural history his hobby. He made detailed studies of the minute anatomy of the caterpillar, and his book *Traité anatomique de la chenille qui rouge le bois de saule* was published in 1760, has been hailed as a monument to outstanding research. A catalogue of his extensive collections was published in 1796, *Catalogue raisonné du célébre cabinet de coquilles de feu P. Lyonet*, The Hague. We have encountered Georges-Louis Leclerc, Comte de Buffon (1707–88), earlier in this chapter. He was one of the most prolific writers on natural history throughout the eighteenth century. He began the vast work *Histoire naturelle* which spanned 44 volumes, the first three of which were published in 1749, the last appearing in 1804. Incomplete drafts of *Les époques de la nature*, dating from 1778, were edited and published by Jacques Roger in 1962. The *Oeuvres complètes de Monsieur le Comte de Buffon* were published in Paris between 1774–89 (145 volumes), while the *Oeuvres philosophiques de Buffon*, edited by Jean Piveteau, were not published until 1955.[24] Albrecht von Haller (1708–77) was also hugely prolific, and showed considerable versatility. Graduating from Leiden in 1727, where he studied under Boerhaave, he became Professor of anatomy, surgery and botany at Göttingen. In 1728 he published *Enumeratio methodica stirpium indigenarum Helvetiae*, Göttingen, followed in 1768 by *Historia stirpium indigenarum Helvetiae inchoate*, Berne, which described 2486 species of plants native to Switzerland. Between 1771–72 he published *Bibliotheca botanica*, two volumes, Berne and Basle; then in 1774–77 he produced *Bibliotheca anatomica*

in two volumes at Zurich. Haller had published a cascade of medical and physiological books at Göttingen: *Icones anatomicae* in eight parts (1743–56); *De respiratione experimentia anatomica* (1746); *Disputationes anatomicae* in seven volumes (1746–52); *Primae lineae physiologicae in usum praelectionum academicarium* (1747). *Elementa physiologiae corporis [etc.]* was published at Berne and Lausanne in eight volumes (1778). His shorter works were published at Lausanne in three volumes: *Opera minora emendata, aucta et renovata* (1762–68).

Thomas Sydenham (1624–89) was an innovative physician, born in Wynford Eagle, Dorsetshire, and educated at the University of Oxford. He described the value of cinchona bark to treat malaria. His *Processus Integri* 1692, published posthumously, became a leading textbook for a generation. Like Hooke and Leeuwenhoek, he is well known for books published during the eighteenth century. *The whole works of that most excellent physician, Dr Thomas Sydenham* (London, 1717) which does not in fact contain the 'whole' works, and the *Opera medica* (Geneva, 1757) which does, reveal him to have been a revolutionary, an outsider and something of a maverick. Bernardino Ramazzini (1633–1714) showed sympathy with such ideas by carrying out the first scientific studies of occupational health. His *De morbis artificum* (Modena, 1700), was published in English as *A treatise on the diseases of tradesmen* (London, 1705). Pathology was effectively launched during this era, with the work of Giovanni Battista Morgagni (1682–1771). He published his great work *De sedibus et causis morborum per anatomen indagatis* (Venice, 1761) when he was eighty. It took the form of letters to a collaborator, describing diseases and relating the process of morbidity to the findings at autopsy. This master-work was published in London in three volumes as *The seats and causes of diseases* (1769). It is a medical classic.

The Hunter brothers William (1718–1783) and John (1728–1793) were born in Long Calderwood, Scotland, and became leading authorities on anatomy. They were also, in later years, rivals. To this day, followers and students of one tend to abhor the other. William studied medicine at Glasgow, graduating in 1750, and became a leading London doctor and lecturer. His best known book is the superbly illustrated *Anatomy of the human gravid uterus, exhibited in figures* (1774). His younger brother John did not study at university, but began adult life as a cabinet-maker. He travelled to London in 1748 to help his brother teach anatomy. He began to read lectures at Surgeon's Hall in 1753 and in 1758 he was appointed surgeon at St George's Hospital, London. He was appointed a surgeon to King George III in 1776. One of his experiments involved self-inoculation with syphilis, which he erroneously believed to be identical with gonorrhoea. His books include: *The natural history of the human teeth* (1771); *A treatise on the venereal disease* (1786); *Observations on certain parts of animal oeconomy* (1786). His *Treatise on the blood, inflammation, and gunshot wounds* was published posthumously in 1794. He had private natural history collections amounting to over 10,000 items which became the nucleus of the

new Royal College of Surgeons.[25] John Hunter's *Observations and reflections on geology [etc.]* written in 1790, was not published until 1859.

In the Netherlands, one of the great anatomists of the age was Bernard Siegfried Albinus (1697–1770) of Leiden. His major works included *Tabulae sceleti et musculorum corporis humani* (1747) and *Tabulae ossium humanorum* (1753), with many illustrations set in 'pictorial' settings.[26] The emerging science of comparative anatomy was greatly advanced through the work of Petrus Camper (1722–89) of Leiden. He compared human and ape anatomy, in 1782 publishing *Naturkundige Verhandelingen over den Orang Outang [etc.]*, Amsterdam, followed by *Dissertation sur les variétés naturelles qui caracterisent la physiognomie des hommes [etc.]* (Paris, 1791) which was translated from the Dutch by H. J. Jansen. James Hutton (1726–97) qualified in medicine in 1749, but turned from medicine and spent two decades travelling. In 1768 he returned to Edinburgh and became a leading member of scientific society and a prime mover of the Scottish Enlightenment.[27] 'Like John Hunter, Hutton was fascinated by geology. In 1785 he read a paper to the Royal Society of Edinburgh entitled *Theory of the earth*. It was published that year as a small anonymous booklet: *Abstract of a dissertation read in the Royal Society of Edinburgh, upon the seventh of March, and fourth of April, MDCCLXXXV, concerning the system of the earth, its duration, and stability*. The paper was published in the *Proceedings*, and gave rise to a major two-volume book published in 1795. Hutton was active in chemistry, strenuously opposing Lavoisier, and also published *An investigation of the principles of knowledge [etc.]*, three volumes (1794) and *Dissertations on the philosophy of light, heat and fire* (1794). His *Theory of the earth* founded the uniformitarian theory of geology, expounding that ground rock in river-beds would eventually become conglomerate strata and return to its original state. It was a 'steady-state' view of geology as a process of eternal recycling. The century saw growing interest in geology in Britain.[28]

John Woodward (1665–1728) was a pioneer of seventeenth-century plant physiology, and became Professor of Physic at Gresham College in 1692. *An essay towards a natural history of the earth* (London, 1695) launched him into a career as a geologist. The book was reprinted in 1702 and 1703. Among his later works were: *Naturalis historia telluris illustrata et aucta*, three parts (1714); *Observations on the different strata of earths and minerals [etc.]* (1727); *Fossils of all kinds digested into a method* (1728); and *An attempt towards a natural history of fossils in England*, two volumes (1728–29). William Whiston (1667–1752) published *A new theory of the earth* in 1696, and the books of Whiston and Woodward opened the century with grand gestures towards the advancement of geology in Britain. William Smith (1769–1839) was a 'navvy', who took to the study of geology from his observations during a career building canals. As the eighteenth century ended, he was beginning to compile the wonderfully detailed geological maps which laid the groundwork for modern geological workers. During the 1790s he listed the strata of England from

Carboniferous to Cretaceous, and began to compile keys to fossils as identifiers. Many books stemmed from this endeavour, including *A delineation of the strata of England and Wales with part of Scotland* (1815) and *Strata identified by organized fossils* (1816–24). Johannes Bartholomäus Beringer (?–1740) was a professor at Würtzburg who published a book entitled *Lithographiae Wirceburgensis* (1726) which revealed startling new discoveries in the neighbouring hills. Nothing like these fossils had been seen before, and indeed they have not been since. Beringer had been the victim of a hoax. Students carved stones to look like grotesque fossil forms, which he realized only when finding a 'new' fossil which had his name neatly carved into it. He attempted to retrieve and destroy every copy of the newly-printed book, and it is on this account extremely rare.

It was in mid-eighteenth century France that the first true geological maps were made. These were the work of Jean Étienne Guettard (1715–86) who travelled 3000 kilometres across central France to delineate its surface geology. In 1746 he gave his first cartographic presentation to the Académie des Sciences. Guettard recognized discrete rocky strata extending from France to southern Britain, and after a visit to Italy in the 1770s concluded that volcanic activity had given rise to the characteristic geology of the Auvergne – an astonishing conclusion to a nation bereft of volcanoes. In 1746 he published his '*Mémoire et carte minéralogique sur la nature et situation des terreins qui traversent la France et l'Angleterre*' in the *Mémoires de mathématique et de physique ... de l'Académie des Sciences*, Paris. Nicholas Desmarest (1725–1815) studied the same regions of France, and took the step of showing that volcanic action had occurred at different epochs. He published '*Mémoire sur la détermination de trois époques de la nature par les produits des volcans*' (1806) in *Mémoires de l'institut des sciences, lettres et arts de l'Académie des Sciences*, Paris. Barthélémy Faujas de Saint-Fond (1741–1819) meanwhile produced a beautiful folio work in 1778, *Recherches sur les volcans étients du Vivarais et de Velay*, Grenoble. Anton Lazzaro Moro (1687–1740) wrote on the origin of the world in *De' crostacei e degli altri marini corpi che si trouvano su monti* (Venice, 1740) and a posthumously published account written by Benoit de Maillet (1656–1738) is contained in *Telliamed ou entretiens d'un philosophie indien avec une missionaire français* (Amsterdam, 1748). Geological investigation was active in Switzerland, where the forces of nature gave much bare and upthrust rock for study. Horace Benedict de Saussure (1740–99) of Geneva coined the term 'geology' in 1779, and wrote *Voyages dans les Alpes*, three volumes (1779–96). He pioneered experimental geology, and attempted to disprove Desmarest's theories about vulcanism. Johann Jacob Scheuchzer (1672–1733) studied fossils, writing *Piscium querelae at vindiciae* (1708) and the influential *Herbarium diluvianum* (1709) which described fossil plants.

Atomic theory began to take its modern form during the eighteenth century. The first book of the self-taught John Dalton (1766–1844) is *Meteorological observations and essays* with two imprints during 1793 in London (a second

edition was not printed until 1834). His atomic theory was contained in *A new system of chemical philosophy* (Manchester and London, 1808–10) but this was not the first modern atomic theory. That was published by the largely forgotten William Higgins (1763–1825), an Irish chemist who published *A comparative view of the phlogistic and antiphlogistic theories [etc.]* (London, 1789) with a second edition in 1791. He anticipated concepts including multiple proportion and valency, and became embittered at the later fame attracted by Dalton. Indeed, his *Experiments and observations on the atomic theory and electrical phenomena* (London, 1814) contains a critique of Dalton's work. Richard Kirwan (1733–1812) was also Irish, a native of County Galway. Educated at Poitiers and Paris, he practised law in Ireland and then moved to London where he pursued interests in science, and was elected an FRS in 1780. He became friendly with Cavendish, Banks and Priestley, publishing *Elements of mineralogy* (1784), *An Essay on phlogiston and the constitution of acids* (1787), *An Essay on the analysis of mineral waters* and *Geological essays* (1799) and *Logic* (1807). His *Essay on phlogiston* was translated into French by Madame Lavoisier.

Chemistry flourished during the eighteenth century, as Enlightenment thinking moved away from alchemy, and the early books on chemical discovery have long been collectors' items. The origins of the new discipline can be discerned through the books of the age. Jean Jacques Manget (1652–1742) published *Bibliotheca chemica curiosa* (1702) in Geneva, as two folio volumes containing 140 tracts on alchemy. It was one of the most comprehensive and well organized accounts of alchemical practice. Few books on alchemy followed. Friedrich Roth-Scholtz wrote a German treatise with a Latin title, *Bibliotecha chemica*, published in 1719 at Nuremberg. He followed it with *Deutsches theatrum chemicum*, a collection of 52 alchemical treatises published at Nuremberg between 1728 and 1732. This marked the demise of alchemy, and allowed chemistry to flourish. We have seen earlier in this chapter that Boerhaave published in the field of chemistry, as well as in natural history, and editions of his *Elementa chemiae* were widely translated and published. These included: Latin (1732) in Leiden, Paris and London; (1733) in Paris; French (1741) in Paris, (1748) The Hague, (1752) Leiden, (1754) in Paris; German (1732–34, 1762, 1782) in Berlin, and English (1733, 1735, 1737) in London. Boerhaave's *Some experiments concerning mercury [etc.]* was reprinted from the Royal Society in 1734, with Latin translations at Utrecht in 1736 and Venice in 1737. There is an exceedingly rare reprint from *Elements of chemistry*, subtitled *Being the annual lectures of Herman Boerhaave, Englished by a Gentleman of the University of Oxford*, which is undated but was actually published in January 1732. William Lewis (1708–81) edited George Wilson's *Complete course of chemistry*, published in 1746, and co-wrote with Alexander Chisholm the *New dispensary* of 1753, a description of experimental chemistry. In Russia, chemistry and physics were advanced by Mikhail Vasilevich Lomonosov (1711–65) who became regarded as the 'founder of Russian science'. He wrote *Oratio de meteoris vi electrica orbis* (1754), and *De origine lucis* (1757), both published in St Petersburg.

We think of Sir James Watt (1736–1819) as the progenitor of an efficient steam engine and an architect of the industrial revolution, but he is also known as a distinguished scientist. Born in Greenock, Renfrewshire, he trained as an instrument-maker in London during 1756–57. He returned to Glasgow as 'mathematical instrument maker to the University'. Watt was active in the Lunar Society of Birmingham. His letters to Joseph Black (*infra*) and his manuscript on heat have been published by Robinson, Eric and McKie, Douglas (1970), *Partners in Science, James Watt and Joseph Black*, London. The first systematic material theory on heat, later known as the caloric theory, was written by William Cleghorn (1754–83). He gained his MD from Edinburgh for a thesis entitled *De igne* (1779). We should also note the Polish-born Daniel Gabriel Fahrenheit (1686–1736) whose thermometric scale dates from 1721, and the Swedish astronomer Anders Celsius (1701–44) who designed a mercury thermometer which led to the adoption of the temperature scale in use today. The original Celsius thermometer, it should be noted, had zero at boiling point and 100° as the freezing-point of water, the reverse of modern convention.

At Uppsala University, Torbern Olaf Bergman (1735–84) contributed to natural history, astronomy, chemistry and physics. His collected papers were published during the eighteenth century as *Opuscula physica et chemica* at Stockholm, Uppsala, Aboe and Leipzig in six volumes, 1779–90. A translation by William Withering. *q.v.*, gave us *Outlines of mineralogy [etc.]* (1783), while other versions appeared in London and Paris. Another noted Swedish chemist was Carl Wilhelm Scheele (1742–86) whose *Chemische Abhandlung von der Luft und dem Feuer* (Uppsala and Leipzig, 1777) and *Opuscula chemica et physica* (Leipzig, 1788–89) have been widely republished in translated editions. A facsimile of the English edition of 1786 was published in 1966.

The first professor of chemistry in Germany was Martin Heinrich Klaproth (1743–1817) who was responsible for several important developments at Berlin. He discovered uranium, zirconium oxide and compounds of titanium during the 1790s. His writings were published in Berlin as *Beiträge zur chemischen Kenntniß der Mineralkörper* (1795), and appeared in London as *Analytical essays towards promoting the chemical knowledge of chemical substances* in 1801. In Saxony, Carl Friederich Wenzel (1740–93) published on chemistry and metallurgy. He made special studies of the actions of acids on metals, and published *Einleitung zur höheren Chymie* (Leipzig, 1774) *Chymische Untersuchung des Flußpaths* (Dresden, 1783) and *Lehre von der Verwandschaft der Körper* (Dresden, 1777–79). Jeremias Benjamin Richter (1762–1807) was a native of Silesia, and introduced the term *stoichiometry* to the study of the proportionality of reacting substances. He is the author of *Aufängsgründe der Stochyometrie oder Meßkunst chemischer Elemente*, three volumes (Breslau and Hirschberg, 1792–94) and *Über die neueren Gegenstände der Chemie* (Breslau, 1791–802). A great British teacher of chemistry was William Cullen (1712–90) who inspired many to investigate this new field. He did not publish, however, though we should note the writings of one of his pupils. With an Irish father and Scottish

mother, Joseph Black (1728–99) was born in Bordeaux and qualified in medicine at Edinburgh in 1754. Of his inaugural dissertation, *De humore acido a cibis orto et magnesia alba*, the *Dictionary of National Biography* says: 'There is, perhaps, no other instance of a graduation thesis so weighted with novelty'. The text, suitably expanded, was to form his first book, *Experiments upon magnesia alba, quick-lime and other alkaline substances [etc.]* (Edinburgh, 1777). It was reprinted in 1782. He also published *Directions for preparing aerated medicinal waters [etc.]* (Edinburgh, 1787) and an edition of his *Lectures on the elements of chemistry, delivered in the University of Edinburgh* appeared in 1803 in Edinburgh and London. Otherwise he wrote little, concentrating instead on teaching. Black originated the concept of 'specific heat', and pioneered quantitative analysis. He recognised carbon dioxide, which he termed 'fixed air'.

Like Cavendish, Priestley and Scheele, Black believed in the phlogiston theory. This held that inflammable bodies were phlogiston-rich, and gave out this substance during combustion. The theory was expounded by Georg E. Stahl (1660–1734) from the seventeenth-century work of Johann Joachim Becher (1635–82). In 1669 Becher claimed to recognize three types of matter: vitrifiable, mercurial and combustible. Stahl coined the term *phlogiston* for the flammable property possessed by the third category. Although the notion has been dismissed as absurd, the supposed movement of phlogiston has a scientific interpretation,[30] for we can relate it to the transfer of electrons during oxidation. At the time it made perfect sense. Stahl's work was *Zufällige Gedancken und nützliche Bedencken über den Streit, von dem so genannten Sulphure* (1718), Halle. The phlogiston theory was resolutely opposed by the creative genius of Antoine Laurent Lavoisier (1743–94) of Paris, who studied law and became a tax-collector before branching out to embrace many other scientific disciplines. At the age of 23 he won a gold medal for an essay on street lighting, and became a member of the Académie des Sciences when just 25 years old. Lavoisier helped Jean Étienne Guettard (*q.v.*) compile his mineralogical map of France. He coined the term *oxygène* and identified atmospheric nitrogen. His extensive writings have been catalogued (see Duveen, D. I. and Klickstein, H. S. (1954), *A Bibliography of the Works of Antoine Laurent Lavoisier [etc.]*, and other publications by the same authors). Lavoisier wrote *Sur la combustion en général* (1777) and *Considerations sur la nature des acides* (1778). His most influential book was *Traitée élémentaire de chemie [etc.]*. It has a chequered publishing history. Some of the first edition was bound as a single volume for the author in 1789, a few copies of which have been found. The formal publication of this edition in Paris was in two volumes. A second edition was published in the same year, 1789, but in three volumes with the third section devoted to Lavoisier's *Méthod de nomenclature chimique*. Eighteenth-century translations were into English, German and Italian. There was also a pirated second edition in Paris in 1793, of which there were three printings. Lavoisier had married the 14-year-old Marie-Anne Paulze who worked with him, assisted at his experi-

ments and drew them up for later publication. She published his autobiographical notes as *Mémoires de chimie* in 1805, after he was executed by revolutionary forces. The two had a wide circle of friends, including Benjamin Franklin and Francis Guillotin, the latter's invention being used to end Lavoisier's life on 8 May 1794. His widow subsequently married the American physicist Benjamin Thompson in 1805.

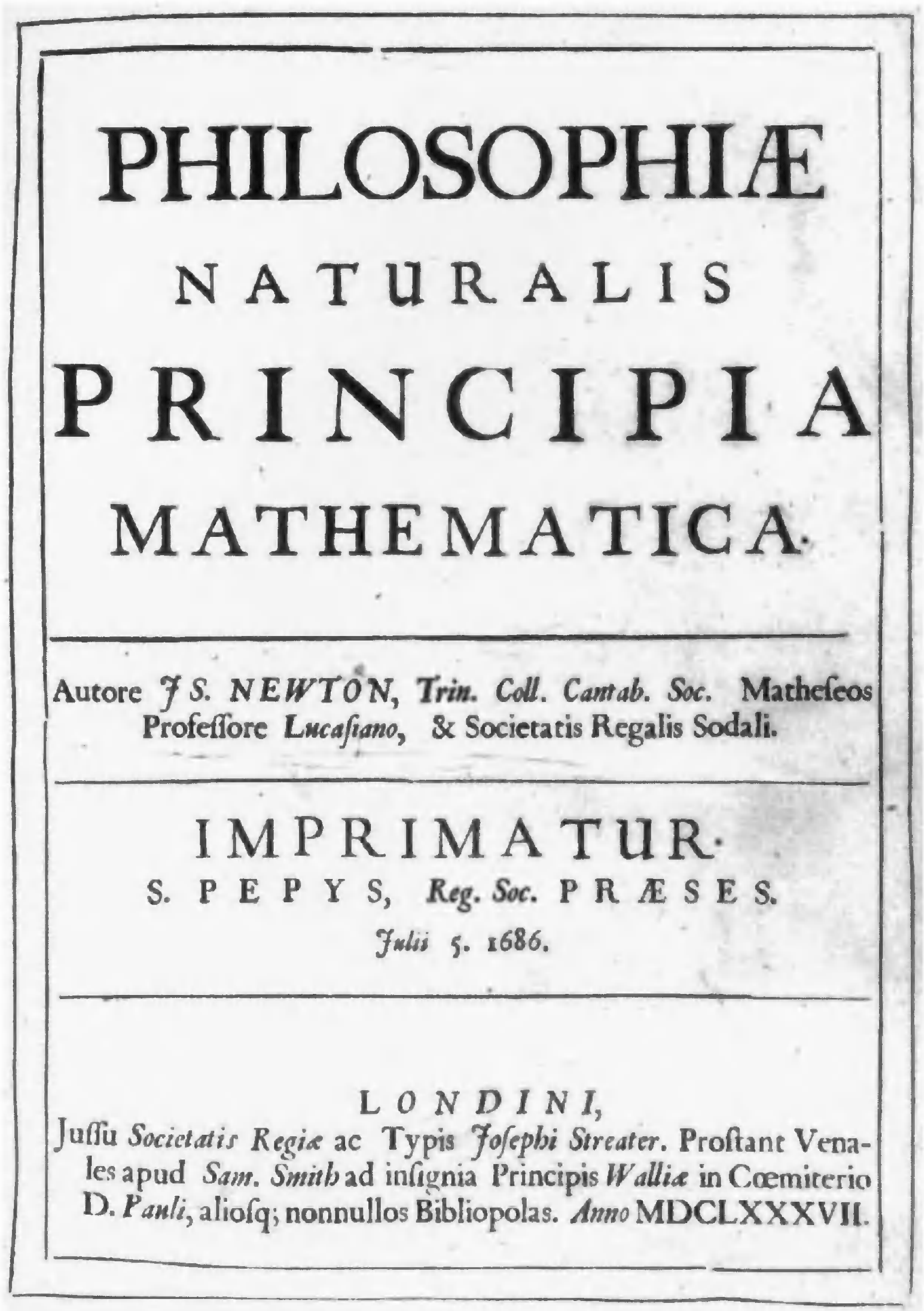
Lavoisier's new chemistry was championed in France by Louis Bernard Guyton de Morveau (1737–1816) who advanced the use of chlorine as a disinfectant. He anonymously published *Discours sur l'etat actuel de la jurisprudence* (1768) in Paris, and at Dijon published *Digressions académiques* (1772) and *Élémens de chymie théoretique et practique*, three volumes (1777). Jean Antoine Chaptal, Comte de Chanteloup (1756–1832) gave the name *nitrogen* to Lavoisier's 'azote'. He promoted agricultural science, and became a government minister in 1800. His books include *Tableau analytique du cours de chymie* (1783) and *Éléments de chimie* (1790), both published at Montpelier. Claude Louis Berthollet (1748–1822), a Parisian professor who travelled with Napoleon to Egypt, wrote *Recherches sur les lois de l'affinité* (Paris, 1801) and *Essai de statique chimique* (Paris, 1803). He introduced chlorine bleaches, also discovering cyanide and hydrogen sulphide. A medical graduate, Antoine François de Fourcroy (1755–1809), turned to chemistry and was an inspirational lecturer and writer. Among his many books are *Leçons élémentaires d'histoire naturelle et de chimie* (1792) *Principes de chimie* (1787), *Analyse chimique de l'eau sulfureuse d'Enghein* (1792), and *Tableaux synoptiques de chimie [etc.]* (1800), all published in Paris. His greatest work was *Système des connaisances chimiques [etc.]* (1801), published in five quarto volumes in Paris. A second edition appeared as eleven octavo volumes during the same year. A graduate of medicine who turned to chemistry was Pierre Joseph Macquer (1718–84) who compiled a dictionary of his discipline. The *Dictionnaire de chymie [etc.]* was twice printed in Paris during 1766, with further editions in differing formats in 1777 and 1778. It was translated into Danish and English (1771), German (1768), and Italian (1783–84). He then published *Élémens de chymie théoretique* (1749, 1753, 1756), and *Élémens de chymie pratique* (1751, 1756), both published in Paris. They were translated into English for publication as *Elements of the theory and practice of chemistry*, two volumes (London, 1758) with a second edition in three volumes (London, 1764), and a third edition (1768) published in Edinburgh. Further English editions appeared in 1775, London, and 1777, Edinburgh. It appeared in German (1768), Dutch (1773, 1775) and Russian (1774–75). Macquer and Antoine Baumé jointly wrote *Plan d'un cours de chymie expérimentale et raisonnée avec un discours historique sur la chymie* (1757), published in Paris.

In Britain, chemistry owed much to the independent spirit of Joseph Priestley (1733–1804), a minister of religion, teacher, and companion to Lord Shelburne, Earl of Lansdowne. He was interested in electricity and studied the respiration of plants. In 1772 he isolated nitric oxide and hydrogen chloride, which he collected by downward displacement of mercury. He discovered the gases we

now know as ammonia in 1773, sulphur dioxide in 1774 and oxygen in 1775. Priestley's work was prolific, largely because of the time allowed for individual study and experimentation by his wealthy patron. His first scientific publication was *The history and present state of electricity, with original experiments* (London, 1767), followed by *A familiar introduction to the study of electricity* (London, 1768) both of which went through several editions. Priestley's book on carbonated mineral waters was *Directions for impregnating water with air, in order to communicate to it the peculiar spirit and virtues of Pyrmont water, and other mineral waters of a similar nature* (London, 1772) but his most important descriptive account of his experiments occurs in *Experiments and observations on different kinds of air* in three volumes (London, 1774–77) which was abridged and republished at Birmingham in 1790. It was followed by a further book covering the series, *Experiments and observations relating to various branches of natural philosophy, with a continuation of the observations on air [etc.]* (London, 1779) which was also re-issued at Birmingham. Later he published in London *Experiments and observations relating to the analysis of atmospherical air* (1796) and *Considerations on the doctrine of phlogiston* (1796) with a final salvo, *The doctrine of phlogiston established*, in 1800.[30]

Isaac Newton (1643–1727) accomplished his greatest work during the seventeenth century, though many of his works flourished during the eighteenth. His *Principia*, as it is known (the original title being *Philosophiae naturalis principia mathematics*) was originally published in 1687, but the second edition appeared in 1713 and the third in 1726, with 25 copies printed on large paper. The 1726 edition was frequently reprinted, and reissued at Glasgow in 1871, with many foreign editions appearing during the eighteenth century. The popular English translation by Andrew Motte appeared in London in 1729, and facsimiles have been published since. Several editions also appeared of his *Arithmetica universalis [etc.]* (Cambridge, 1707) and *The method of fluxions and infinite series [etc.]* (London, 1736). Newton's *Opticks, or, a treatise of the reflexions, refractions, inflexions, and colours of light [etc.]* was first published in 1704 in London, with further editions in 1717 and 1718. His collected works first appeared as *Opera mathematica, philosophica et philologica [etc.]* in Switzerland, and in London as *Opera quae exstant omnia [etc.]* (1779–85). For all his strength in science, it is intriguing to reflect on Newton's unabated interest in alchemy and spiritualism.

Robert Smith (1689–1768) studied at Trinity College, Cambridge, where his cousin Roger Cotes (1682–1716) was Plumian Professor of Astronomy. Smith succeeded his cousin in this position. He wrote *Harmonics* (1748) and the *Compleat system of opticks in four books* (1738) both published at Cambridge. Johann Heinrich Lambert (1728–77) was the Swiss German mathematician who first proved that π was an irrational number. He also published on the nature of light, in *Photometria, sive de mensura et gradibus luminis, colorum et umbrae* (Ausburg, 1760). Pierre Bouger (1698–1758) was a professor of hydrology in Brittany, but published *Essai d'optique sur la gradation de la lumière* (1729),



PHILOSOPHIÆ

NATURALIS

PRINCIPIA

MATHEMATICA.

Autore *J S. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.

S. PEPYS, *Reg. Soc.* PRÆSES.

Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtant Venales apud *Sam. Smith* ad inſignia Principis *Walliæ* in Cœmiterio D. *Pauli*, alioſq; nonnullos Bibliopolas. *Anno* MDCLXXXVII.

7. Newton, *Philosophiae naturalis principia mathematica* (1687).
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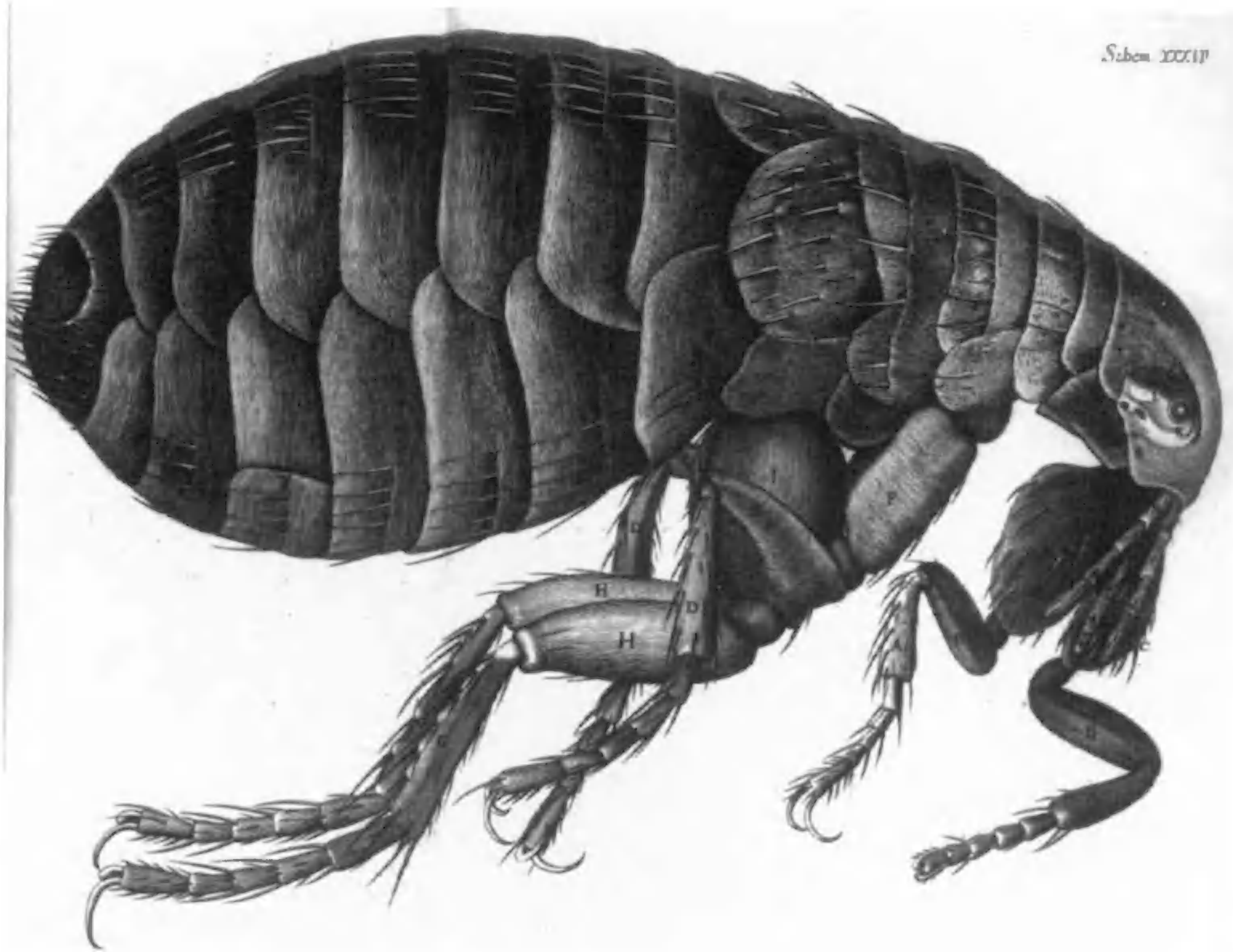
reissued posthumously as *Traité d'optique sur la gradation de la lumière* (1760). A visit to Peru in 1735 gave him an opportunity to measure the earth's meridian at the equator, described in *Figure de la terre déterminée* (Paris, 1749).

The progress of science has always owed much to the independent investigator. The Honourable Henry Cavendish (1731–1810) was eccentric, retiring and shy; yet his work is confident, assured and prolific. Cavendish was wealthy, and devoted his time to the furtherance of the sciences. Many of his papers were published in *Philosophical Transactions* (the first, 'On factious airs', appeared in 1766). During the eighteenth century his output continued apace, and his papers were later published as collections. The first of these was Maxwell, J. Clerk (1879), *The electrical researches of the Honourable Henry Cavendish FRS [etc.]*, Cambridge, which included many accounts appearing for the first time in print. This was followed in the twentieth century by Thorpe, Sir Edward (1921), *The scientific papers of the Honourable Henry Cavendish FRS [etc.]*, Cambridge. The assistant to Cavendish was Charles Blagden (1748–1820) who began his career as an army surgeon but became the Secretary to the Royal Society. His researches (like those of Cavendish) appear as papers in the *Philosophical Transactions*. In the United States, Benjamin Franklin (1706–90) was the greatest innovator of the time; indeed he was one of the world figures of eighteenth century science. He began as a trainee printer, and in middle age became prominent in politics (he served as American ambassador to Paris). He was always interested in experimentation, of which his well-known capture of electricity by means of a kite flown in a thunderstorm is just one example. He was lucky not to have been killed; a Russian researcher died in an attempt to repeat the demonstration. The appearance of this unfortunate individual's internal organs after a *post-mortem* examination was widely discussed throughout Russia. Many of Franklin's papers appeared in the *Philosophical Transactions* in London. Franklin corresponded with the British investigator Peter Collinson (1696–1768) who later became eminent as a botanist. The letters were published between 1751–53 as *Experiments and observations made at Philadelphia in America*. This was followed by *Part II: Supplemental experiments* (1753) and *Part III: New experiments and observations* (1754), all published in London. The second edition in English, published in two volumes, was *New experiments and observations on electricity* (1754) while the third edition, published in three volumes – with the third wrongly identified as the fourth on the title page – appeared between 1760–65. Further English editions appeared in 1769 and 1774. French editions were published in Paris (1753, 1756 and 1773), an Italian edition appeared in Milan in 1774, and the German translation was published in Leipzig dated 1758. There have been many modern works on Franklin, and these show his extensive correspondence with fellow-scientists. He collaborated with Lavoisier (*q.v.*) in research on explosives, the balloon, and animal magnetism.[31]

Research into electrical phenomena in France was greatly advanced by the work of the Abbé Jean Antoine Nollet (1700–70), who gave the Leyden jar its

name. Nollet published *Lettres sur l'électricité dans lesquelles on examine les découverts [etc.]* (Paris, 1753) of which an Italian version had been published in Venice in 1747. He also wrote *Recherches sur les causes particulière des phénomenes électrique [etc.]* (1754), *Essai sur l'électricité des corps* (1746) and *L'Art des expériences sur ... la construction et l'usage des instruments [etc.]* in three volumes (1770), all published in Paris. Charles Augustin Coulomb (1736–1806) is known for the eponymous unit of electrical charge. His work on electricity was facilitated by his invention of the torsion balance, which he used to measure the strength of attraction and repulsion between charged bodies. His *Théorie des machines simples* was presented to the Académie des Sciences in 1784, a new edition being published in Paris in 1820. Francis Hauksbee the elder (?–1713) is a vague figure in British research on electricity. He was mentioned by Newton in correspondence, and carried out experiments on friction-induced static electricity. He also invented a serviceable vacuum-pump. Hauksbee published a collection of papers in *Physico-mechanical experiments on various subjects* (1709) with a further posthumous edition in 1719. Stephen Gray (1667–1736) carried out crucial work on electrical conductivity and insulation. He is regarded as the father of electrical communication. Little is known of his life, though he became a pensioner of the London Charterhouse. His 21 papers were published in *Philosophical Transactions*. John Freke (1688–1756), was a surgeon at St Bartholomew's Hospital, London (see: Chalstrey, John (1957). 'The life and works of John Freke (1688–1756)', *St Bartholomew's Hospital Journal*, 61, 85–89, 108–112). Freke wrote *An essay to show the cause of electricity and why some things are non-electricable [etc.]* (London, 1748) which ran to three editions. It was later expanded and reprinted as *A treatise on the nature and property of fire* (1752), also published in London. The popularity of electricity, as a topic of study, was widespread. In Italy, Luigi Galvani (1737–98) noticed a frog's leg move convulsively during dissection with a scalpel. He concluded, with some presumption, that 'in the animal itself there was an in-dwelling of electricity'. He communicated his observations to the Bologna Academy of Science in 1791, and printed the tract in Bologna that same year as *De viribus electricitatis in motu musculari*. A German translation was published in Prague as *Abhandlung über die Krafte der thierischen Elektrizität auf die Bewegung der Muskeln* (1793). The state of optics in Britain is well covered by the great book of Robert Smith (1689–1768), Master of Trinity College, Cambridge, and Plumian Professor of Astronomy. The title-page of his wide-ranging *Complete system of opticks in four books [etc.]*, published in 1738 in Cambridge, also describes him as 'Master of Mechanicks to His Majesty'. This became perhaps the most influential textbook on optical sciences published during the period.[32]

Although astronomy occupied many of the greatest eighteenth-century minds, surprisingly few major books devoted to the subject were published. John Bradley (1693–1762) was a friend of Halley and Newton, and in *Philosophical Transactions* he published accounts of comets and the aberration of light. They



8. Hooke, *Micrographia* (1665)
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were collected together and published as Rigaud, S. P. (1832), *Miscellaneous works and correspondence of the Rev. James Bradley*, Oxford. Bradley was Astronomer Royal from 1742–62. In 1763, the *British mariner's guide* was published by Nevil Maskelyne (1732–1811), and he was appointed Astronomer Royal in 1765. He launched the *Nautical Almanac* in 1767: it is still produced annually. He was fascinated by eclipses, and later measured the lateral defelction of a plumb-line caused by mountains. This work allowed him to calculate that the density of the earth lay between 4.56–4.97 that of water (the modern value is 5.52). Thomas Wright (1711–86) was a follower of Newton. A native of Durham, he published a major work on navigation, *Pannauticon* (1734) which has since virtually disappeared. His *Universal vicissitude of seasons* appeared in 1737, of which only one copy is known. Wright's later books included *The use of globes* (1740), a popular book on astronomy entitled *Clavis coelestis [etc.]* (1742), *Louthiana* (1749) on the antiquities of the Irish county of Louth. His *Original theory or new hypothesis of the universe [etc.]* (1750) embodied a revolutionary theory on the nature of the Milky Way. It was first published in London, with a second edition being published in the United States in 1837. Wright's final book was *The longitude discover'd without use of graduated instruments* (1773). Thomas Wright's idea influenced the philosopher Immanuel Kant (1724–1804) who wrote *Allgemeine Naturgesischte und Theorie des Himmels [etc.]* (1755), published in Konigsberg and Leipzig. Later editions appeared in 1798, 1890 and 1908. An English translation of Kant's book was published in Glasgow (1900) as *Kant's Cosmogony, as in his essay on the theory of the heavens. With introduction, appendices and a portrait of Thomas Wright of Durham.*[33]

From Scotland came James Ferguson (1710–76), son of a labourer and himself at one time a shepherd. He was initially self-taught and was much excited by watching his father use a lever when raising the fallen roof of their cottage. After being placed in service he was found drawing maps of the heavens using beads on a string, and was given tuition by his master's butler. Later he supported himself as a portrait painter, and was introduced to the Secretary of the Royal Society because of the success of his orbital models. From 1768 King George III regularly invited him to discuss scientific matters. Ferguson lectured widely in London and published many popular works on astronomy. These include: *The astronomical rotula* (1741), which was extensively reprinted; *Description and use of the astronomical rotula* (1775) and *Astronomy explained upon Sir Isaac Newton's principles* (1756) which went through new editions and reprints until 1821.

The best known of eighteenth-century astronomers were the German-born Friederich Wilhelm Herschel (1738–1822) and his co-worker on astronomy, his sister Caroline Lucretia (1750–1848). William, as he became known after moving to England in 1757, trained in music. In 1766 he was appointed organist and music master at the Octagon Chapel in Bath. He was an active performer and composer, and carried out astronomical research in his spare time. His

sister Caroline was believed by their father Isaac to possess great talents but his wife Anna would have none of it, and insisted all her daughters embarked on a strenuous routine of manual domestic duties. In England, however, Caroline was encouraged by her brother and she made many important discoveries in astronomy. Her *Catalogue of stars* (1798) printed for the Royal Society in London is a milestone. William's greatest discovery was published as *Account of a comet* (1781), also printed for the Royal Society. The 'comet' turned out to be the planet Uranus, the first of the outer planets to be discovered with the aid of a telescope. Caroline, in truth one of the most diligent of eighteenth-century astronomical research workers, is usually downgraded to the role of assistant (or even omitted altogether) in many reference works on astronomical science.

There are several French astronomers of the period whose works have endured. Nicholas Louis de la Caille (1713–62) led an expedition from Paris to the Cape of Good Hope in 1750, and published two major works in Paris during 1763: *Journal historique du voyage fait au Cap de Bonne-Ésperance*, and his influential *Stellarum australium catalogus (coelium astrale stelliferum)*. His major book was *Astronomiae fundamenta* (Paris, 1757) with the positions of over 400 of the brightest stars. De la Caille was perhaps the greatest of all French astronomers.[34] A co-worker, Joseph Jérôme le Français de la Lande (1732–1807), was sent to Berlin to carry out observations correlated with those of de la Caille in the southern hemisphere. De la Lande's *Traité d'astronomie* (1764) went into several editions, while his masterpiece entitled *Histoire céleste Français* (1802) catalogues over 47,000 stars. The most prominent eighteenth-century astronomer in France was a peasant farmer's son from Normandy, Pierre Simon (1749–1827), marquis de Laplace. He showed mathematical talents at military academy in Beaumont, and soon moved to Paris where d'Alembert recommended him for a professorship at the École Militaire. He published his celebrated nebular hypothesis in *Exposition du système du monde* (1796) and then produced an immense five-volume work, *Mécanique céleste* (1799–1825). His *Oeuvres complètes* cover fourteen volumes and were published between 1878 and 1912. Bernard le Bovier de Fontenelle (1657–1757) published on astronomy in the seventeenth century, but his eighteenth century biographies of French scientists are among his most valuable bequests to the modern scholar. The 69 *Éloges* were published in Paris as *Histoire de l'Académie Royal des Sciences, avec les Mémoires, [etc.]* (1744) in two volumes. A selection was published in Paris in 1883. [See also: McKie, Douglas (1957), 'Bernard le Bovier de Fontanelle, FRS (1657–1757)', *Notes & Records of the Royal Society of London*, 12, 193–200.]

Rudjer Josip Boskovic (1711–87) was born in Ragusa (then in the territory of Venice, now Dubrovnic, Croatia). He is latterly known as Roger Joseph Boscovitch, and produced over 2000 letters and 180 manuscripts on astronomy, philosophy, optics and mechanics. Boscovich developed theorems for calculating the day length of a planet based on three observations of its surface feature, and for calculating a planet's orbit based on three observations of its position.

He was also a pioneer of atomism, proposing that matter was composed of point-centres of force. He went to Rome in 1725, and published his major work *Philosophiae naturalis theoria redacta ad unicam legem vivium in natura existentium* in 1758 at Vienna.[35] In London, a prominent mathematician named John Harris (c. 1666–1719) wrote several collections of sermons and popular books on geography and astronomy. He is best known for a remarkable state-of-the-art compilation, *Lexicon technicum, or, an universal English dictionary of arts and sciences [etc.]* (1704). It was printed in London as a magnificent folio volume, published by subscription. Supplementary volumes appeared in 1710 and 1744.

The Swiss family Bernoulli produced several great mathematicians.[36] Jacob Bernoulli (1654–1705) was a native of Basle and systematized the Leibniz calculus. His principle work was published in Basle as *Ars conjectandi* (1713). His brother was Johann (or Jean) Bernoulli (1667–1748) who succeeded Jacob in the chair of mathematics at Basle, and whose *Lectiones mathematicae de methodo integralium* (written in 1691–92) was published in 1742. His second son was Daniel Bernoulli (1700–82) who was professor of mathematics at St Petersburg before returning to Basle. His *Hydrodynamica* (1738) was published at Strasbourg. A pupil of Johann Bernoulli became perhaps the greatest mathematician of the era. He was Leonhard Euler (1707–83) who travelled in Russia and Germany. He lost the sight of his right eye through the use of a telescope on the sun, but when he became totally blind in old age found his mathematical work went on unabated. He was prodigiously able to undertake complex mental calculations. Euler introduced the use of π in geometry, i for imaginary numbers and Σ for summation. There were many eponymous introductions: Euler's constant, Euler's equations, Euler's line and Euler's variables. He advanced trigonometry and brought differential calculus to the form we know today. Euler's *Methodus inveniendi lineas curvas* (1744) published in Lausanne reveals him as a gifted expositor. His protégé was Joseph Louis Lagrange (1736–1813) who had taught himself mathematics as a youth and was appointed professor of mathematics at the artillery school in Turin when just 19 years old. He had conceived the heart of his great work *Mécanique analytique* by 1755, and sent the work to Euler, who wrote back expressing his delight and held back his own publications so that Lagrange could take precedence. The *Mécanique analytique* was completed by 1782, but not published until 1788. Lagrange, who said he was greatly influenced as a child by the work of Edmund Halley (1656–1742), went on to persuade the French commission to adopt a base of 10, and not 12, for future standards. In this manner he became the father of the metric system.

A native of Toulouse, Adrin Marie Legendre (1752–1833) wrote on astronomy and mechanics as well as mathematics, his main work being on ellipsoids. His *Éléments de geométrie* (1794) and the *Essai sur la théorie des nombres* (1798) were published in Paris. The first decades of the nineteenth century saw a continuing output of his influential books on pure and applied mathematics.

Meanwhile, Jean Etienne Montucla (1725–99), from Lyons, documented the history of mathematics at Paris. First he published *Histoire des recherches sur la quadrature du cercle* (1754) and then his two-volume *Histoire des mathématiques* (1785) which was reissued in a new edition as four volumes between 1799–1805. Probability was intensively studied by Abraham de Moivre (1667–1754) who wrote *The doctrine of chances, or a method of calculating the probability of events in play*. The first edition appeared in 1718, with further editions in 1738 and 1756. He also wrote *Miscellanea analytica de seriebus et quadraturis* (1730) which appeared in later editions with supplemental pages. A pioneering survey of British mathematicians from 1714 to 1840 found over 2000 names recognized as significant. Eva Taylor's 1966 book, *The Mathematical Practitioners of Hanoverian England 1714–1840*, Cambridge, gives brief bibliographies of 2282 British mathematicians. See also: Wallis, R. V. and Wallis, P. J. (eds) (1993), *Index of British Mathematicians, Part 3, 1701–1800*, Newcastle-upon-Tyne.

Brook Taylor (1685–1731) founded the calculus of infinite variables, and in 1708 deduced a solution to the problem of centre of oscillation. On its publication in May 1714 his priority was unjustly disputed by the elder Johann Bernoulli. In 1715 he published *Methodus incrementorum directa et universa*, which announced 'Taylor's theorem' solving the expansions of functions of a single variable in infinite series. The profound importance of his development was not fully appreciated until Joseph Louis Lagrange (q.v.) drew attention to its significance in 1772. Thomas Simpson (1710–61) applied mathematics to problems of astronomy and physics in his *New treatise on fluxions* (1737). He was also to publish *Nature and laws of chance* (1740) and *Doctrine of annuities and reversions* (1742). Colin Maclaurin (1698–1746) was a Scottish prodigy who became professor of mathematics at the Marischal College, Aberdeen, when aged 19, and later moved to Edinburgh University. His books included *Geometria organica* (1720), *Treatise on fluxions*, in two volumes (1742), and two posthumous books, *Treatise on Algebra* (1748) and *An account of Sir Isaac Newton's Philosophy* (1748). Mathematical research (initially into elliptical integrals) brought a surveyor from Peterborough to fellowship of the Royal Society in 1766. He was John Landen (1719–90), described as the 'English D'Alembert', whose books included *Mathematical lucubrations* (1755)[36] and *Discourse concerning the residual analysis* (1758). *The residual analysis* (1764) was intended to be in several parts; in the event only Book I was published by public subscription. Finally he published *Mathematical memoirs [etc.]*, volume 1 appearing in 1780, and volume 2 being delivered to the author's death-bed on 14 January 1790. He died the next day. He was not personally popular; indeed his private papers were sold for use as wrapping-paper by the shopkeepers of Peterborough, rather than being conserved. Landen was known to the public through his articles in *The Ladies' Diary*, a periodical founded by John Tipper of Coventry in 1704. Articles on the sciences for women were far more popular in earlier centuries than they are today.

Descriptive geometry was advanced by Gaspard Monge (1746–1818), a native of Beaune who eventually became Professor at the École Polytechnique in Paris. His work appeared as *Géometrie descriptive* (1798). Mention must also be made of the philosopher-economist Adam Smith (1723–1790) for his application of scientific principles and mathematical concepts to the problems of an industrialized society. He was brought up by a mother who spent much time educating his mind, and was studying Latin by the age of ten. He remained very close to his mother, greatly valuing her early influence.

Born in Scotland, and educated at University in Glasgow and Edinburgh, Adam Smith formed a close alliance with another Scottish philosopher David Hume (1711–76) with whom he cooperated until Hume's death. Smith's first great book was the *Theory of Moral Sentiments* (1759). His analytical work *An Inquiry into the Nature and Causes of the Wealth of Nations* was published in two volumes (1776) with a second edition in 1778. The third revised edition in 1784 was published in three volumes. Other editions followed, the ninth marking the end of the century. This publication marked the launch of a science of economics.

The nineteenth century was to see a breathtaking maturation of these new sciences. Descriptive science developed to a high degree, complex life histories were studied and the splendour of chemistry was brought together into a conceptual whole. Observational microscopy offered images which are rarely equalled in present-day studies. The institutionalization of science began to reveal the extent to which personal self-perpetuation would come to predominate, and the ultra-specialized technician would introduce schisms that kept the disciplines apart. Our current era has lost sight of the free-wheeling insights that advance our knowledge, for much of our so-called science is technology with social pretensions. True science cannot be restrained within disciplinary boundaries. The interdisciplinary sciences flourished wondrously in the eighteenth century, as they need to do again in the twenty-first. By a perusal of these historic books, with all their quirks and foibles, we may yet learn lessons that can equip today's workers in the fields of science for the urgent problems they will need to tackle tomorrow.

Notes

1. Reference may be made to the *Dictionary of National Biography* (Oxford, 1975) *Encyclopedia Britannica*, 15th edn (Chicago, 1974–95); to Fox, C., Porter, R. and Wokler, R. (1995), *Inventing Human Science: Eighteenth-century domains*, London and Los Angeles; Bruno, L. C. (1987), *The Tradition of Science*, Washington, DC: Library of Congress; also to the *Hutchinson Dictionary of Scientific Biography* (Oxford, 1994), though many distinguished individuals are curiously omitted from the last.
2. For a survey of books on popular aspects medicine, see Porter, Roy (ed.) (1992), *The Popularization of Medicine 1650–1850*, London/New York.

3. See Frängsmyr, Tore, Heilbron, J. L. and Rider, R. E. (eds) (1990), *The Quantifying Spirit in the Eighteenth Century*, Berkeley/Los Angeles; also Cunningham, Andrew and Jardine, Nicholas (eds) (1990), *Romanticism and the Sciences*, Cambridge/New York.
4. 'The individuals that are ranked into one sort, called by one common name, and so received as being of one species,' wrote John Locke (1632–1704), *An Essay concerning Human Understanding*, published in 1690. Twenty editions of this essay, subsequently revised and enlarged, were published by the end of the eighteenth century.
5. Linnaeus published several works, apart from those on taxonomy. All are sought-after by collectors. *Bibliotheca botanica* (1736), published in Amsterdam, includes *Fundamenta botanica, pars 1*, with separate pagination and a dedicated title-page. It was reprinted as *Bibliotheca et fundamenta botanica* (Munich, 1968). *Philosophia botanica* (1751) is a textbook of taxonomy, setting out the Linnaean methodology, with some volumes bearing a title-page from Amsterdam [see Guédès, Michel (1968), 'L'Édition originale de la *Philosophia botanica* de Linné', *Journal of the Society for the Bibliography of Natural History*, 4, 385–89]. *Flora Lapponica* (1737) records the botanical investigations of his Lapland journey of 1732. Linnaeus' diary of this voyage, then in the possession of J. E. Smith, was published in an English translation as *Lachesis Lapponica* (1811). *Hortus Cliffortianus* (1738) describes the garden plants of George Clifford, a merchant with whom Linnaeus stayed in the Netherlands, while the *Flora Suecica* (1745) and *Fauna Suecica* (1746) list methodically the species found in Sweden. *Critica Botanica* (1737) was published in English by the Ray Society in 1938. The *Genera Plantarum*, 5th edn (1754) was published in facsimile, with annotations, in *Historiae Naturalis Classica* (1961) edited by William Stearn. See also: Bryk, P. (1954), 'Bibliographia Linnaeana ad *Genera Plantarum* pertinens', *Taxon*, 3, 174–83; Hulth, Johan Marcus (1907–) *Bibliographica Linnaeana [etc.]*, Uppsala; *A catalogue of the works of Linnaeus issued in commemoration of the 250th anniversary of the birthday of Carolus Linnaeus 1707–78* (Stockholm, 1957); Williams, Terrence (1964), *A check-list of Linnaeus 1735–1835 in the University of Kansas Libraries*, Lawrence; Soulsby, B. H. (1933), *A catalogue of the works of Linnaeus (and publications more immediately relating thereto) preserved in the libraries of the British Museum (Bloomsbury) and the British Museum (Natural History) (South Kensington)* 2nd edn, London; Blunt, W. (1971), *The Compleat Naturalist, a life of Linnaeus*, London; Frängsmyr, Tore (1993), *Linnaeus, the Man and his Work*, Uppsala, rev. edn 1994, Canton, Mass: Science History Publications. The library of Linnaeus and his original specimen collections are preserved in the Linnean Society of London.
6. Staff of Carnegie Institute of Technology (1963–64), *Adanson: the Bicentennial of Michel Adanson's 'Familles des Plantes'*, Pittsburgh.
7. See: Stevens, Peter F. (1994), *The Development of Biological Systematics: Antoine-Laurent de Jussieu, Nature, and the Natural System*, New York.
8. Anker, Jean, (1951), 'The early history of Flora Danica', *Libri*, I, 334–50. See also the same author's *Otto Friderich Müller's Zoologia Danica* (1950), Library Research Monograph vol. 1, Copenhagen University Library.
9. See Sarmiento, F. J. P. (1988), *La ilusión quebrada: Botánica, sanidad y política científica en la España Ilustrada*, Barcelona/Madrid, also Lozoya, Xavier (1984), *Plantes y luces en México, la Real expedición científica a Nueva España* (Barcelona, 1787–1803), and Pérez, Joaquín and Tascón, Ignacio (eds) (1990), *Ciencia, técnica y estado en la España Ilustrada*, Madrid.
10. A review of encyclopAedias of the period may be found in Kafker, Frank A. (ed.) (1994), *Notable Encyclopedias of the Late Eighteenth Century*, Oxford/Paris.
11. Sir Joseph Banks (1743–1820) was a powerful figure of the era. He made few

original discoveries, and was not drawn to publishing, but facilitated a great expansion in the natural sciences. For one of many recent sources, see O'Brian, Patrick (1993), *Joseph Banks, a Life*, Boston, Mass.

12. See Keevil, J. J. (1933), 'William Anderson, master surgeon', *Annals of Medical History* 2nd series, 5, 511–24. Reference may also be made to: Smith, Bernard W. (1992), *Imagining the Pacific, in the Wake of the Cook Voyages*, New Haven, Conn/London.
13. Ford, Brian J. (1994), *Images of Science, a History of Scientific Illustration*, London, pp. 106–7.
14. For publications on Captain James Cook see also New South Wales Library (1928), *Bibliography of Captain James Cook RN, FRS, circumnavigator*, Sydney; Muir, John (1939), *The Life and Achievements of Captain James Cook [etc.]*, London & Glasgow; Roberts, Stanley (1947), 'Captain Cook's voyages, a bibliography of French translations 1772–1800', *Journal of Documentation*, 3, 160–76; Holmes, Sir Maurice (1949), 'Captain James Cook', *Endeavour*, 8, 11–17; Holmes, Sir Maurice (1952), *Captain Cook RN FRS, a bibliographical excursion*, London; Thrower, W. R. (1951), 'Contributions to medicine of Captain James Cook FRS RN', *Lancet*, II, 215–19; Spence, Sydney (1960), *Captain James Cook RN (1728–79), a bibliography of his voyages, to which is added other works relating to his life, conduct and nautical achievements*, Mitcham; Stevenson, Allan (1961), *Catalogue of botanical books in the collection of Rachel McMasters Miller Hunt (II) Printed books 1701–1800*, Pittsburgh, Hunt Botanical Library, lists 764 original botanical works of the period plus 62 facsimiles.
15. Curtis published many other titles, including *Instructions for collecting and preserving insects, particularly moths and butterflies* (1771); *Linnaeus' Fundamenta entomologiae [etc.]* (1772); *Linnaeus' system of botany* (1777); *Short history of the brown-tail moth* (1782) [reprinted in facsimile as the first of the series *Classica Entomologica* (1969)]; *General observations on the advantage which may result from the introduction of the seeds of our best grasses* (1787). *A catalogue of the plants growing wild in the environs of London* (1774) was published anonymously, and it has been suggested that this may also have been written by Curtis.
16. Lamarck was not the sole proponent of such theories. See Corsi, Pietro (1988), *The Age of Lamarck – Evolutionary Theories in France 1790–1830*, Berkeley/Los Angeles.
17. The agricultural sciences were well documented during the century. The first spongiform encephalopathy to be recognized, scrapie, was well documented in 1759 in a paper by Leopold in Germany, heralding current preoccupations with bovine spongiform encephalopathy [see Ford, Brian J. (1996), *BSE: The Facts*, London]. From Edinburgh in 1788 appeared Thomas Thopham's *A new compendious system on several diseases incident to cattle [etc.]*, which gives a wide-ranging summary of diseases in cattle and horses. A catalogue of British authors in agriculture was published in Weston, Richard (1773), *Tracts on practical agriculture and gardening [etc.]*, second edition, London. The first edition had appeared in 1769, but lacked the valuable authors' list. An analysis of agricultural economics was published as Young, Arthur (1770), *Farmer's guide to hiring and stocking farms*, London.
18. See McNeil, Maureen (1987), *Under the Banner of Science, Erasmus Darwin and his Age*, Manchester. It should be noted that the concept of 'natural selection' was introduced by neither Darwin. The publication which introduced this concept was Wells, William Charles (1818), *Two essays: one upon single vision with two eyes ... and an account of a female of the white race of mankind [etc.]*, London.
19. Wolff, C. F., (1768–69), 'De formatione intestinonum', *Novi comentarii academiae scientarium imperialis Petropolitanae*, 12, 403–507; 13, 478–530. These papers

were translated by Johann Friedrich Meckel (1761–1833) and published as *Über die Bildung des Darmkanals in bebruteten Hühnchen* (Halle, 1812).

20. The first two-volume work on psychiatry was also published during this century. Thomas Arnold's *Observations on the nature, kinds, causes, and prevention, of insanity*, was published at Leicester in 1782–86. It is also noteworthy for establishing the custom of providing references to quoted literature. For reviews of publishing in psychiatry during this period see Porter, Roy (1987), *Mind-forg'd Manacles – a History of Madness in England from the Restoration to the Regency*, Cambridge, Mass; and Chiarugi, Vincenzo (1987), *On Insanity and its Classification*, trans. George Mora, Canton, Mass.
21. Renard's drawings were authoritatively dismissed as 'crudely drawn and barbarously coloured' in Dean, B. (1923), *Bibliography of Fishes*, vol. 3, New York. However, when they are published in juxtaposition with more realistic images, as in Hiroshi Aramata's book *Fish of the World* (New York, 1990) resemblances can be discerned between Renard's illustrations and the species they are intended to represent, although most are grossly caricatured. In a comprehensive assessment, Theodore Pietsch now concludes that the book has scientific merit, for almost all the portrayals can be identified. The work, published by the John Hopkins University Press in 1995, is entitled *Fishes, Crayfishes and Crabs, Louis Renard's Natural History of the Rarest Curiosities of the Seas of the Indies*. Volume 1 retells the background to the book while volume 2 is a facsimile in colour, showing Renard's distorted view of reality at its most vivid.
22. See Dobell, Clifford (1932), *Antony van Leeuwenhoek and his 'little animals'*, London; Ford, Brian J. (1985), *Single Lens, Story of the Simple Microscope*, London and New York; and idem (1992), *Leeuwenhoek Legacy*, Bristol and London.
23. See, for example, Andry de Boisregard, N. (1700), *De la génération des vers dans le corps de l'homme [etc.]*, Paris; Corti, Bonaventura (1774), *Osservazione microscopische sulla Tremella e sulla circolazione dell fluido [etc.]*, Lucca; Eichorn, J. C. (1775), *Beyträge zur Naturgeschichte der kleinsten Wasser-Thiere [etc.]*, Danzig; von Gleichen, W. F. [called Russworm] (1778), *Abhandlung über die Saamen und Infusionthierchen und über die Erzeugung [etc.]*, Nürnberg; Ledermüller, Martin F. (1760–65), *Mikroskopische Gemüths- und Augen-Ergötzung*, Beyreuth; Lesser, F. C. (1738), *Insecto-theologia oder ... Versuch wie ein Mensch durch Betrachtung deren sonst wenig geachteten Insecten [etc.]*, Leipzig.
24. See also: Roger, Jacques (1989), *Buffon, un philosophe au Jardin du Roi*, Paris.
25. Findlay, David (1990), *The Hunterian Society, a Catalogue of its Records and Collections [etc.]*, London. See also LeFanu, William (1946), *John Hunter: a List of his Books*, London.
26. See Hale, R. B. and Coyle, T. (1988), *Albinus on Anatomy*, New York.
27. See also Stewart, M. A. (ed.) (1990), *Studies in the Philosophy of the Scottish Enlightenment*, Oxford.
28. Challinor, J. (1953–54), 'The early progress of British geology', *Annals of Science*, 9, 124–53; and 10, 1–19, 107–48.
29. Ford, Brian J. (1971), The March of Science, *History of the English Speaking Peoples*, 6: 2592–2595, London: Purnell, 6 January. A review of the proponents of each side is in: Schneider, Hans-Georg (1992) *Paradigmenwechsel und Generationenkonflikt, eine Fallstudie zur Struktur wißenschaftlicher Revolutionen*, Frankfurt am Main. See also: Anderson, R. G. W., and Lawrence, Christopher, (eds) (1987), *Science, medicine and dissent, Joseph Priestley (1733–1804)*, London.
30. See: Cohen, I. Bernard (1990), *Benjamin Franklin's Science*, Cambridge, Mass/London.

31. See also Hall, Rupert (1993), *All Was Light: an Introduction to Newton's Optics*, Oxford.
32. See also Gulyga, Arsenij (1987), *Immanuel Kant, his Life and Thought*, trans. Marijan Despalatovic, Boston/Basel/Stuttgart, and Melnick, Arthur (1989), *Space, Time and Thought in Kant*, Dordrecht/Boston/London. The development of physical astronomy during the German Enlightenment has been the subject of scholarly research. See Baasner, Rainer (1987), *Das Lob der Sternkunst, Astronomie in der deutschen Aufklärung*, Göttingen.
33. See Evans, David S. (1992), *Lacaille, Astronomer, Traveler; with a New Translation of his Journal*, Tucson, Ariz.
34. See Whyte, L.L., (ed.) (1961), *Joseph Boscovich S.J., F.R.S., 1711–87: Studies of his life and work on the 250th anniversary of his birth*, London. Also Dadic, Zarko (1987), *Rudjer Boscovic*, Zagreb, and Supek, Ivan (1989), *Rudjer Boscovic, vizionar u prijelomima filosofije, znanosti i drustva*, Zagreb.
35. The catalogue of family members distinguished in mathematics is Jacob Bernoulli (1654–1705), Johann Bernoulli (1667–1748), Nicholas Bernoulli (1685–1759), Nicholas Bernoulli (1695–1726), Daniel Bernoulli (1700–82), Johann Bernoulli (1710–90), Johann Bernoulli (1744–1807) and Jacob Bernoulli (1759–89), who jointly left over 7500 letters.
36. A *lucubration* is, literally, study by artificial [in this case candle- or lamp-] light; in general usage, nocturnal studies.

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Chapter Seven

Books on the Natural Sciences in the Nineteenth Century

Frank A.J.L. James

Introduction

Between 1800 and 1899 the content of science changed profoundly. In physics at the start of the century the Newtonian orthodoxy, of rectilinear forces acting in aetherless space through which light particles travelled, on the whole prevailed. By 1899 the work of the Dutch physicist Hendrik Lorentz (1853–1928) on space–time, the discovery by the English physicist Joseph John Thomson (1856–1940) of a sub-atomic particle (later named the electron) and much else besides were pointing the way towards the physics of the twentieth century. In chemistry during the nineteenth century atomism was established (though not without considerable controversy), the modern system of chemical symbols was developed, and crucial concepts such as that of valency were enunciated. In the biological and earth sciences in 1800 most still thought in terms of special creation; by 1899, while there was still considerable dispute over the precise mechanism of evolution and over how much time needed to be allowed for the process, it was generally believed that evolution had occurred and that the earth was considerably older than apparently allowed for by the Bible.

Many of these changes in science, especially in the middle two quarters of the century and especially in the physical, biological and earth sciences, occurred in Britain. At the beginning of this period, Charles Babbage (1791–1871) wrote in his *Reflections on the Decline of Science in England and on some of its causes* (London, 1830) that he was not optimistic about the position of science in Britain compared with its position on the Continent. He highlighted issues such

as the perceived lack of government funding for science. But largely because of its industrial and consequent imperial power as well as because of its geological structure, Britain was in fact well placed during the nineteenth century to be the location for far-reaching developments in science. The roles played by those who worked at the Royal Institution in London, at Oxford or Cambridge Universities or at the Scottish universities were crucial in this process. Much important scientific knowledge was also produced in France, the German-speaking states and to a lesser extent in the Italian states, especially as they became increasingly industrialized. In France most scientific research throughout the nineteenth century was conducted by those working in the various élite institutions based in Paris. In the German states, the intense competition between the universities of those states led to the pursuit of excellence, with quite small universities able to become world-class centres of research such as, for example, Giessen and Heidelberg in chemistry. The pattern thus established was continued after Unification and by 1899 the science base of the German Empire was very strong indeed, especially in chemistry, but also in physics; it was in Germany, after all, that modern physics was created.

The expansion of science which occurred during the nineteenth century was, of course, reflected in the books that were written and the catalogue of the British Library lists 9658 books published between 1800 and 1899 as containing the keyword 'science' or one of its cognates. In a similar way 'physics' has 2570 entries, chemistry 4948, astronomy 2041, biology 435, geology 3882, physiology 2533 and Naturwissenschaft 629. These figures exclude those books which only have a scientific term in their titles such as 'species', 'electricity', 'optics', etc. There is clearly some overlap between all these categories and, in addition, new editions of texts such as the *Physics* of the ancient Greek philosopher Aristotle (384–322 BC) also appear in them. Furthermore, though the collection of the British Library is enormous, there are significant gaps, particularly in the area of non-British science books. Thus during the nineteenth century a large, but indeterminate, number of books on scientific subjects was published – probably far more than all science books published before 1800.

Evidently, then, it is impossible within the compass of a short essay to deal thoroughly with this mass of material. It can only be approached generally by statistical methods and by impressionistic accounts of the development of the scientific book based largely on what historical research has shown to be important in the development and communication of science. But first I want to paint a statistical portrait, also impressionistic, of how the publishing of science books changed during the nineteenth century.

Science books in London, 1800–99

'Lies, damned lies, and statistics' as the nineteenth-century Tory Prime Minister Benjamin Disraeli (1804–81) was reported as saying by the American writer

Mark Twain (1835–1910). Statistics, by their necessary reliance on numbers, can lend a false air of precision and objectivity to the conclusions drawn from them. But the validity of such conclusions is entirely dependent on the quality of the data – or, to put it into modern idiom, GIGO (garbage in, garbage out). Thus little or no attention should be paid to the actual numbers given below, since they are certainly not precise. What should be significant are the trends that they reveal, which the imprecisions in the data do not (I hope) affect.

Because of the incompleteness of the collection of the British Library, we cannot use it as a whole to analyse satisfactorily patterns in the publication of science books. I have therefore chosen to examine books published in London on a decade by decade basis during the nineteenth century. This choice was governed by three reasons. First, I assume that the British Library's collection of books published in London is fairly complete. Second, it excludes English language science books published abroad in say the United States or the colonies. Third, London was the place of publication of a large number of the books published during the nineteenth century in the holdings of the British Library. This proportion for any decade never fell below a quarter and was never higher than a third. The size of the statistical example is large enough to render significant (rather than random) the trends that emerge.

Table 1 gives the data (not to be taken as precise) of the total number of books published per decade in London, the incidence of the occurrence of various keywords of scientific books published in London followed (in parentheses) by the percentage that they contribute to the overall number of books published in London during that decade.

A striking feature is the constancy of the absolute number of books published in London containing the keywords 'natural' and 'philosophy'. Never higher than 33 in any decade and never lower than 14, the proportion of books published on natural philosophy fell fairly steadily during the century so that by 1899 their number was quite insignificant. On the contrary, books containing the keyword 'science' not only generally increased in absolute numbers, but also as a proportion until the 1870s when it began to decline. Both 'biology' and 'physics' (a term which many men of science did not like) were rarely used terms in nineteenth-century books. 'Geology' and 'physiology', on the other hand, were terms that found increasing favour during the century until mid-century following which their use (both in absolute and proportional terms) began to decline. 'Astronomy' books, though their absolute number remain fairly constant, show a marked falling off in proportion beginning in the 1850s. Books containing the word 'chemistry' or those containing either 'geometry' or 'mathematics' both tended to an increase in absolute numbers (and thus a stability in proportion). Towards the end of the century there was an increase in proportion in chemistry books which presumably reflected the increased usefulness of chemistry for technological purposes. In a similar way, and presumably for similar reasons, 'electricity' showed a proportionate increase towards the end of the century.

Table 1. Books on scientific subjects published in London, 1800–99. Figures in parentheses represent percentages.

Decade total	London	'Natural Philosophy'	'Science'	'Mathematics' and 'Geometry'	'Astronomy'	'Physics'	'Chemistry'	'Geology'	'Biology'	'Physiology'	'Electricity'
1800–09	12741	28(0.22)	54(0.42)	23(0.18)	18(0.14)	1(0)	31(0.24)	2(0.02)	0	10(0.08)	7(0.05)
1810–19	15654	23(0.15)	74(0.47)	29(0.19)	27(0.17)	1(0)	32(0.2)	14(0.09)	0	26(0.17)	5(0.03)
1820–29	20201	27(0.13)	125(0.61)	49(0.24)	43(0.21)	4(0.02)	44(0.22)	24(0.19)	0	47(0.23)	9(0.04)
1830–39	24457	26(0.11)	182(0.74)	43(0.18)	36(0.15)	7(0.03)	50(0.2)	48(0.2)	0	66(0.27)	16(0.07)
1840–49	30511	23(0.08)	190(0.62)	69(0.23)	53(0.17)	12(0.04)	86(0.28)	73(0.24)	2(0)	78(0.26)	20(0.07)
1850–59	42279	33(0.08)	315(0.75)	41(0.1)	68(0.16)	9(0.02)	86(0.2)	99(0.23)	7(0.02)	64(0.15)	25(0.06)
1860–69	42012	18(0.04)	463(1.1)	64(0.15)	55(0.13)	9(0.02)	69(0.16)	88(0.21)	5(0.01)	60(0.14)	14(0.03)
1870–79	45840	28(0.06)	541(1.18)	74(0.16)	55(0.12)	27(0.06)	97(0.21)	79(0.17)	7(0.02)	76(0.17)	27(0.06)
1880–89	51699	22(0.04)	505(0.98)	87(0.19)	37(0.07)	31(0.06)	130(0.25)	91(0.18)	16(0.03)	78(0.15)	81(0.16)
1890–99	56797	14(0.02)	522(0.92)	93(0.16)	51(0.09)	58(0.1)	196(0.35)	71(0.13)	35(0.06)	87(0.15)	99(0.17)

Source: British Library CD-ROM Catalogue

Many factors contributed to these trends in the publishing of science books. Some of these had to do with developments in science, but there were also reasons within the publishing trade and with the demand for science books in both the general market and the scientific community. It is to the changing nature of scientific publication during the nineteenth century that we will now turn.

The change in scientific writing

The communication of novel scientific knowledge in the nineteenth century between scientific practitioners can be characterized, without overly great simplification, as the move from books to papers. Behind this characterization of scientific books in the nineteenth century there lies, of course, a great deal of diversity, not only between the individual sciences (as the statistics show), but also within them and between countries. The move from books to papers reflects the changing social structure of science during the nineteenth century. There were more people doing science in 1899 than there were in 1800, there were more universities, there were more academies and, most importantly from the point of view of the book, there were more scientific periodicals.

In Britain or France during much of the eighteenth century the only effective way of publishing new scientific work was either by publishing a book, or by securing publication of a paper in the *Philosophical Transactions* of the Royal Society (founded in London 1665) or the *Histoire de l'Académie Royale des Sciences* (founded in Paris in 1699), neither of which, however, published more than a book-length volume each year. However, towards the end of the century some new journals were founded. These included: *Observations sur la Physique*, later renamed the *Journal de Physique* (founded Paris 1773), the *Transactions of the Royal Irish Academy* (founded Dublin 1787), the *Transactions of the Royal Society of Edinburgh* (founded Edinburgh 1788), the *Annales de Chimie* (founded Paris 1789), the *Transactions of the Linnean Society* (founded London 1791), the *Bibliothèque Universelle* (founded Geneva 1796), *Nicholson's Journal* (founded London 1797), the *Philosophical Magazine* (founded London 1798) and the *Annalen der Physik und Chemie* (founded Leipzig 1799 and edited in succession by the German physicists Ludwig Wilhelm Gilbert (1769–1824) and then by Johann Christian Poggendorff (1796–1877) after whom the journal was generally eponymously known). Some of these new journals, especially the transactions of the learned societies, were occasional publications, which in terms of pages did not absorb that much material. However, journals such as the *Philosophical Magazine* and the *Annalen der Physik* were monthly and took up a good deal of material. Such periodicals also had the great advantage of (normally) being able to publish scientific results much more quickly than a book could do and in the form of a short paper which books could not do.

In the early part of the nineteenth century further journals were founded. These included the *Transactions of the Geological Society* (founded London

1811), the *Annals of Philosophy* (founded London 1813), the *Quarterly Journal of Science* (which ran from 1816 to 1831 and was closely related to the Royal Institution), the *Edinburgh Journal of Science* (founded 1824) and the *Edinburgh Philosophical Journal* (founded 1826). With this proliferation of scientific journals in the early nineteenth century there were too many journals chasing too little science. Translations of papers between different language journals abounded, as did summaries of papers appearing in other journals and reports of meetings and lectures. In addition editors frequently had to commission articles in order to keep their pages full. One of the consequences of this over-supply of journals was that some journals merged and others closed. However, as the century progressed, the quantity of scientific results requiring publication expanded vastly, thus bringing to an end the problems that scientific journals had experienced earlier in the century. Indeed the expansion in the number of scientific results which required publication necessitated an ever-increasing number of journals. This increase included the start of the weekly scientific press with the *Comptes Rendus* (founded Paris 1835 and which was restricted to reporting the proceedings of the Académie des Sciences), *Chemical News* (founded London 1859) and *Nature* (founded London 1869). The 19-volume Royal Society Catalogue of nineteenth-century scientific papers published between 1867 and 1925 is a monument to the increased importance of the scientific paper and of the scientific journal during the nineteenth century.

The expansion of scientific journals during the century meant that there was an increase in competition between books and these new channels for communicating scientific knowledge quickly and effectively. Nevertheless, as the statistics show, books were able to maintain a strong position in the communication of science throughout the century. And it was not just in the areas of textbooks and popular science books, where it might be expected that the book would maintain its position, but the book also retained its role in communicating new science. Many important books containing new scientific knowledge and new insights were published during the nineteenth century. In Britain one only has to think of the *Principles of Geology* (1830–33) by the geologist Charles Lyell (1797–1875), or the *Origin of Species* (1859) by the naturalist Charles Darwin (1809–82) or the *Treatise on Electricity and Magnetism* (1873) by the physicist James Clerk Maxwell (1831–79), to name but three, to realize that many important books of original research and ideas were published during the century. But these examples do not invalidate the overall notion that new scientific results were increasingly published in periodicals. Here we have only to think of the work of the English chemist and natural philosopher Michael Faraday (1791–1867) on electricity and magnetism which was mostly published in the *Philosophical Transactions,* or the seminal papers on thermodynamics by the Scottish natural philosopher William Thomson (1824–1907), or the papers by the German chemist Robert Bunsen (1811–99), to realize that, in general, the short paper became the preferred form of communication between men of science.

But there was an interesting consequence for the scientific book market in the publication of papers in journals. This was the rise of the book of collected papers which began quite early in the nineteenth century. The papers and books of the British chemist Humphry Davy (1778–1829) were collected together as a nine-volume set published in 1839 and 1840 by his brother John (1790–1868). Davy's erstwhile protégé at the Royal Institution, Faraday, himself collected most of his papers together into four volumes published between 1839 and 1859. These editions were later joined by collected editions of many of the most eminent (and some less eminent) men of science of the nineteenth century. These collected papers included those written by Thomson and by Maxwell, as well as the English natural philosopher Thomas Young (1773–1829), the French engineer and physicist Augustin Jean Fresnel (1788–1827), the Anglo-Irish mathematician George Gabriel Stokes (1819–1903), the German physicist Gustav Robert Kirchhoff (1824–87), the Mancunian physicist James Prescott Joule (1818–89), the relatively obscure Scottish physicist John James Waterston (1811–83) and many others. Such collections of papers in book form rendered the scientific community (and later the history of science community), a great service by allowing relatively easy access to papers published in sometimes, obscure or not easily obtained journals. Furthermore, collected editions also made available papers in major journals which new members of the scientific profession would not necessarily have immediately to hand.

How to study science and how science had developed were the subject of a number of books. For instance the polymathic English man of science John Herschel (1792–1871) in his *A Preliminary Discourse on the Study of Natural Philosophy* (London, 1830) and the Cambridge philosopher of science William Whewell (1794–1866) in his *The Philosophy of the Inductive Sciences, founded upon their History* (2 volumes, London, 1840) sought to understand how natural phenomena ought to be studied. Herschel's text in particular was influential in a number of sciences with individuals as diverse as Faraday and Darwin acknowledging its value. Whewell in his *History of the Inductive Sciences, From the Earliest to the Present Times* (3 volumes, London, 1837) sought to describe how science had developed until the 1830s and as such can be seen as one of the foundation texts showing that there was a subject called the history of science.

The publication of new science

The study of science by Herschel, Whewell and others told them that the model science to which all other sciences should aspire was astronomy, underpinned as it was by accurate observations and the principles of Newtonian mechanics as modified by the French mathematician Pierre Simon de Laplace (1749–1827) in his *Traité de Mécanique céleste* (5 volumes, Paris, 1798–1827). Since astronomy was the model science, many astronomical texts were simply catalogues of

observations, such as that of the German astronomers Johann Bode (1747–1826) in his *Uranographia, sive astrorum descriptio viginti tabulis aeneis incisa ex recentissmis et absolutissmis astronmorum observationibus* (Berlin, 1801) and Friedrich Bessel (1784–1864) in his *Fundamenta astronomiae* (Königsberg, 1818) or the French astronomer Joseph de Lalande (1732–1807) in his *Histoire céleste française* (Paris, 1801), and Herschel's *Results of Astronomical Observations, made during the years 1834, 5, 6, 7, 8 at the Cape of Good Hope; being the completion of a telescopic survey of the whole surface of the visible heavens, commenced in 1825* (London, 1847). But Herschel also wrote his *Treatise on Astronomy* (London, 1833) which was aimed at a more general audience. It was not until after astronomers turned their attention away from positional astronomy and towards examining the chemical and physical constitution of the stars and planets, made possible by the 1859 work of Bunsen and Kirchhoff on spectroscopy, that new types of astronomy books, such as that by the English astronomer J. Norman Lockyer (1836–1920) *The Chemistry of the Sun* (London, 1887), began to appear.

Closely linked with the development of both astronomy and physics was mathematics. In the area of rigorous analysis the French mathematician Augustin Louis Cauchy (1789–1857) laid the foundation of the theory of functions in his *Cours d'analyse algébrique* (Paris, 1821), while the logic of mathematics and indeed of thought generally was developed in texts such as *Formal Logic* (London, 1847) by the English mathematician Augustus De Morgan (1806–71), *The Mathematical Analysis of Logic* (Cambridge, 1847) and *An Investigation of the Laws of Thought, on Which Are Founded the Mathematical Theories of Logic and Probabilities* (London, 1854) both by the Anglo-Irish mathematician George Boole (1815–65) and *Symbolic Logic* (London, 1881) by the English mathematician John Venn (1834–1923). Arguably more important in the development of scientific thought in during the nineteenth century was a greater understanding of probability and statistical theory which allowed for the reduction of large quantities of data over a wide range of sciences. Laplace's *Théorie analytique des probabilités* (Paris, 1812) increased the power of probability theory while the German mathematician Carl Friedrich Gauss (1777–1855) in his *Theoria combinationis observationum erroribus minimus obnoxiae* (Göttingen, 1823) improved the method of least squares, and the French physicist Siméon Poisson (1781–1840) in his *Recherches sur la probabilité des jugements* (Paris, 1837) helped develop the theory of probability distribution.

In physics, or natural philosophy, the overarching theoretical structure was dominated by Newtonianism both in mechanics and optics (whatever interpretation was attached to that structure). Very few important books, other than textbooks, were published in these areas. However, heterodox views on the nature of light were given an airing in books such as *Zur Farbenlehre* (2 volumes, Tübingen, 1810) by the German writer Johann Wolfgang von Goethe (1749–1832) in which he argued, without too much success, against the Newtonian view of optics.

In other areas of physics, books were an important medium of communicating new scientific ideas. For example the French physicist N.L. Sadi Carnot (1796–1832) in his *Réflections sur la puissance du feu et sur les machines propres à développer cette puissance* (Paris, 1824) gave the first text to analyse physically how a steam engine worked and stated what later became recognized as an early version of the second law of thermodynamics. However, it was not until the 1840s that Thomson discovered this text and recognized the importance of Carnot's work – perhaps had he published it in a journal his work would have been more widely known earlier. Another important text on heat was by the French mathematician Jean Joseph Fourier (1768–1830) who in his *Théorie analytique de la chaleur* (Paris, 1822) applied mathematical functions to analysing the behaviour of heat passing through bodies, again an idea that was taken up by Thomson. In the work, during the 1830s and 1840s, of English natural philosophers such as Joule, Thomson, Faraday and William Robert Grove (1811–96), of German physicists such as Hermann Helmholtz (1821–94) and Julius Robert Mayer (1814–78) and others, the principles of the interrelation, conservation and dissipation of energy were established and refined. Some of this work received contemporary expression in texts such as Grove's *On the Correlation of Physical Forces* (London, 1846). Thomson and his colleague, another Scottish natural philosopher Peter Guthrie Tait (1831–1901), synthesized the consequences of the new science of thermodynamics in their *Treatise on Natural Philosophy* (Oxford, 1867).

In the relatively new sciences of electricity and magnetism, books occasionally played an important role in reporting new scientific work. For instance the French physicist André-Marie Ampère (1775–1836) in his *Théorie des phénomènes électrodynamiques uniquement déduite de l'expérience* (Paris, 1826) collected together the results of his work on electro-magnetism, while what became Ohm's law was published by the German physicist Georg Ohm (1789–1854) in his *Die galvanische Kette, Mathematisch bearbeitet* (Berlin, 1827). Gauss in his *Intensitas vis magneticae terrestris ad mensuram absolutam revocata* (Göttingen, 1832) not only drew attention to the importance of studying terrestrial magnetism (which was thus influential in the negotiations surrounding the magnetic crusade of the late 1830s and 1840s) but also promoted the use of cgs units as a systematic way of measuring physical quantities. The summation of the immense quantity of work on electricity and magnetism came with the publication of Maxwell's *A Treatise on Electricity and Magnetism* (2 volumes, Oxford, 1873). In this text he developed a new theory which eventually transformed the understanding of the physical world from that of Newtonian forces to that of field theory which had been proposed by Faraday. One of the consequences of Maxwell's work was the possibility that signals could be sent across distances without the need for wires. This idea was taken up by a number of physicists including, in Germany, Heinrich Hertz (1857–1894) who in his *Untersuchungen ueber die Ausbreitung der elektrischen Kraft* (Leipzig, 1892) brought Maxwell's work up to date, resulting in experiments which led to the invention of radio.

What is particularly striking is that, in general, important books in physics dealt with newer branches such as heat, electricity or magnetism, rather than with older branches such as optics or mechanics. In the case of optics it was expected by their contemporaries that Herschel or Stokes would write a monograph on the subject, but these never materialized and they preferred to publish their work in journals. On the other hand the understanding of acoustics (always the poor relation of physics) in the nineteenth century was to a much larger extent dealt with in books such as Helmholtz's *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (Braunschweig, 1863) and by the English aristocrat and physicist John William Strutt, 3rd Lord Rayleigh (1842–1919) in his *The Theory of Sound* (2 volumes, London, 1877–78) rather than in journals.

Chemistry at the beginning of the nineteenth century was still in a considerable state of flux following the work of the French chemist Antoine Laurent Lavoisier (1743–94) and many books were written which developed an overarching view of the subject. The Mancunian chemist John Dalton (1766–1844) in his *A New System of Chemical Philosophy* (2 volumes, London, 1808–27) promoted a version of chemical atomism which was not taken up widely until much later in the nineteenth century, though textbooks such as *A System of Chemistry* (3rd edition, 5 volumes, Edinburgh, 1807) by the Scottish chemist Thomas Thomson (1773–1852) incorporated Dalton's views into already existing texts. Davy, who was dismissive of Daltonian atomism, argued in his *Elements of Chemical Philosophy* (London, 1812) that chemical and electrical forces were identical. Most chemists, however, in their books preferred to take a descriptive rather than a theoretical position. Thus the French chemist Claude Berthollet (1748–1822) in his *Essai de statique chimique* (Paris, 1803) described how chemical reactions happened, while the Swedish chemist Jöns Jacob Berzelius (1779–1848) in his *Lärbok i kemien* (Stockholm, 1814) gave currency to his system of chemical nomenclature with which we are so familiar today (that is, Fe is the symbol for iron, C for carbon etc., with appropriate numbers used to indicate the chemical composition of compounds). Berzelius's system was given a great boost when it was used by Edward Turner (1796–1837), the first Professor of Chemistry at University College London, in his *Elements of Chemistry* (4th edition, London, 1833) and thereafter it entered into everyday chemical use. Chemistry was also used in a biological context to help undermine the doctrine of vitalism. A particularly important text in this context was *Chimie organique fondée sur la synthèse* (2 volumes, Paris, 1860) by the French chemist P.E. Marcellin Bertholet (1827–1907). On the disciplinary borders of chemistry and physics is crystallography, involving as it does the interaction between light and arrays of chemical molecules. One of the foundation texts of crystallography was *Traité de minéralogie* (4 volumes, Paris, 1801) by the French crystallographer René-Just Haüy (1743–1822). Thereafter, as with so much chemistry and physics, crystallographic work was generally reported in journals. Although the vast bulk of chemical work was published in

journals, there were a number of important books published, which either provided an overarching theory, or especially in the case of textbooks, were crucial in securing the acceptance of new approaches to the study and communication of chemistry.

In the earth and life sciences, books were, for the most part, more important than journal articles as a place to publish both data and theories. With the expansion of European hegemony over the rest of the world, data collection was carried out in the process of exploration of the new European possessions. Much of this work was sponsored in one way or the other by the military establishments of the countries involved. Most famously was the round-the-world voyage by Darwin on HMS Beagle between 1832 and 1836. This resulted directly in the publication of his *Journal of Charles Darwin, Naturalist to the Beagle (1832–1836)* (London, 1839) and his *The Geology of the Voyage of the Beagle* (3 volumes, London, 1842–46). Other texts with military or imperial connections which gathered together natural historical data include *Prodromus florae novae Hollandiae et insulae van Diemen* (London, 1810) by the British botanist Robert Brown (1773–1858) and by the Director of the Royal Botanic Gardens, Kew, Joseph Hooker (1817–1911) in his *The Botany of the Antarctic Voyage of H.M. Discovery-Ships Erebus and Terror, in 1839–1843* (6 volumes, London, 1844–60) and his *The Flora of British India* (London, 1875–97). This process culminated in the *Report on the Scientific Results of the Voyage of H.M.S. Challenger during the years 1873–76*, the zoological section of which alone ran to 32 volumes published between 1885 and 1889. In addition further data was accumulated in texts such as *Recherches sur les ossemens fossiles* (4 volumes, Paris, 1812) by the French comparative anatomist Georges Cuvier (1769–1832), which helped found comparative palaeontology, in *Recherches sur les poissons fossiles* (5 volumes, Neuchâtel, 1833–43) by the Swiss-American geologist Louis Agassiz (1807–1873) and in *Descriptive and Illustrated Catalogue of the Physiological Series of Comparative Anatomy* (5 volumes, London, 1833–40) by the English comparative anatomist Richard Owen (1804–92).

But the collection and publication of such vast quantities of data meant that some sort of order and understanding needed to be applied to them. In the early part of the nineteenth century, there was no general agreement about the history of the earth. The Scottish mathematician and geologist John Playfair (1748–1819) promoted uniformitarian geology in his *Illustrations of the Huttonian Theory of the Earth* (Edinburgh, 1802), but this theory did not meet with immediate acceptance. Part of the problem was related to the status of fossils and whether species in the past had changed into other species. In his *Systême des animaux sans vertèbres* (Paris, 1801), the French zoologist Jean Baptiste Lamarck (1744–1829) suggested that organic evolution had occurred. In later books he developed this theory by arguing that offspring inherited the characteristics which their parents had acquired and which thus drove evolution. The English geologist William Smith (1769–1839) in his *Stratigraphical System of Organized Fossils* (London, 1817) associated particular fossils with particular

geological strata which implied, at the very least, a sequence of species development. But such views were implicitly opposed in texts such as *Reliquiae diluvianae: or Observations of the Organic Remains Contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, Attesting the Action of a Universal Deluge* (London, 1823) by the Oxford geologist William Buckland (1784–1856), in which he insisted on the importance of the Biblical Flood as an important causal element in earth history.

Lyell's *Principles of Geology, being an Attempt to Explain the Former Changes of the Earth's Surface by Reference to Causes now in Operation* (3 volumes, London, 1830–33) argued carefully for an uniformitarian view of the history of the earth. Darwin took volume one with him on the Beagle which greatly influenced the development of his views during the voyage. One consequence of Lyell's work was to promote the study of various geological problems and areas such as that undertaken by the retired British army officer and geologist Roderick Murchison (1792–1871) in his *The Silurian System* (London, 1839) and by Agassiz in his *Etudes sur les glaciers* (Neuchâtel, 1840). The former unravelled the strata of what became known as the Silurian period, while the latter examined the role of glaciers in earth history. Such geological work also gave rise to more general studies of the environment in texts such as *The Philosophy of Storms* (Boston, 1841) by the American meteorologist James Espy (1785–1860) and *The Physical Geography of the Sea* (London, 1855) by the American oceanographer Matthew Maury (1806–73). These texts are taken to be the foundation studies in meteorology and oceanography respectively.

Organic evolution continued to be canvassed by various individuals during the 1840s and 1850s, receiving controversial support from the Scottish publisher Robert Chambers (1802–71) in his anonymous *Vestiges of the Natural History of Creation* (London, 1844). Implicitly opposing evolution, Owen in his *On the Archetype and Homologies of the Vertebrate Skeleton* (London, 1848) argued that species followed particular divinely created archetypes. However, starting with the publication of Darwin's *On the Origin of Species by means of Natural Selection* (London, 1859) and his later book-length studies including *The Variation of Plants and Animals Under Domestication* (2 volumes, London, 1868) and *The Descent of Man and selection in relation to sex* (2 volumes, London, 1871), he firmly established evolution, and to a lesser extent natural selection, as the overarching biological theory. The most controversial aspect of Darwin's work was that man had evolved from animals rather than being specially created. The place of man in nature received much attention following 1859 in texts such as Lyell's *The Geological Evidences of the Antiquity of Man* (London, 1863), *The Great Ice Age and its relation to the antiquity of man* (London, 1874) by the Scottish geologist James Geikie (1839–1915) and in books written by the English eugenicist Francis Galton (1822–1911) especially his *Hereditary Genius* (London, 1869) and *Natural Inheritance* (London, 1889).

Running in parallel with the development of understanding of the earth and of evolution, there was also a more experimental study of plants and animals.

For instance the German biologist Theodor Schwann (1810–82) elaborated his cell theory in *Microskopische Untersuchungen über die Uebereinstimmung in der Struktur und dem Wachsthum der Thiere und Pflanzen* (Berlin, 1839), a theory that was taken up by another German biologist Rudolph Virchow (1821–1902) in his *Die Cellularpathologie* (Berlin, 1858). But most important in this area was the French experimental physiologist Claude Bernard (1813–1878) who in his *Introduction à l'étude de la médecine expérimentale* (Paris, 1865) forcefully argued for the use of experimental method in the study of physiology – a position he was able to take because of his experimental discoveries of the function of the pancreas and of the liver, among other organs.

Though the scientific paper increased in importance as a means of communication during the nineteenth century, it is clear both from the statistics and from many of the examples cited above that the book retained, and arguably augmented, its role as a communication route between men of science.

Science books in culture

Of course not all science books were intended to communicate new science to other members of the scientific community. Some were explicitly intended to communicate the results of scientific endeavour to a broader readership. Some were written to inspire an interest in science together with some limited instruction. Instances of these include *Conversations on Chemistry* (London, 1805) by the Anglo-Swiss author Jane Marcet (1769–1858) and *The Fairly-Land of Science* (London, 1879) by the English writer Arabella Buckley.

Professional men of science also wrote texts aimed at a wider readership. One such was the German naturalist Alexander von Humboldt (1769–1859) who in his *Kosmos, Entwurf einer physichen Welteschriebung* (5 volumes, Stuttgart and Tübingen, 1845–62) sought to provide a synthesis about what was already known about the universe. Other texts written by scientific practitioners sought to promote a particular interpretation of scientific knowledge. For instance the eight Bridgewater Treatises, written by savants including Whewell and Buckland, published during the 1830s tried to show 'The Power Wisdom and Goodness of God as Manifested in the Creation'. Due to the special pleading they contained, these books conspicuously failed to come anywhere near achieving their aim and indeed these kinds of natural theological arguments fell out of fashion thereafter. At the opposite end of the theological argument, the German biologist Ernst Haeckel (1834–1919) in *Die Welträthsel* (Bonn, 1899) right at the end of the century argued that science had shown that only matter was real. On a more practical level, texts such as *A Manual of the Steam Engine and Other Prime Movers* (London, 1859) by the Scottish engineer William Rankine (1820–72) provided a popular account of thermodynamics designed to show the value of science for engineering purposes.

Though this essay has concentrated mainly on books written to communicate scientific knowledge between practitioners, it should be noted that one of the great virtues of books is that anyone, not just specialists, can read them. The same, of course, goes for journals, but these were less accessible to a general audience than many books. Science books played a major role in ensuring that for much of the nineteenth century science played an important role in general culture – much more so than today. There were frequently several columns devoted in the pages of the weekly press to scientific matters – reports of lectures, reviews of books and so on. The quarterlies like the *Edinburgh Review* and the *Quarterly Review* frequently contained substantial articles on scientific subjects. With such a widespread interest in science it was natural that not only would science books be written especially for a broad audience, but that some authors at least would take care to make their work as accessible as possible. Works like Darwin's *Origin of Species* was not simply a piece of research written by one scientific practitioner for his peers; it was meant to be read by a general educated audience. On the other hand texts such as Maxwell's *Treatise on Electricity and Magnetism* with its formidable mathematical equations could only have been intended for a specialist readership.

The fact that the scientific book survived the rise of the journal and indeed flourished is a testament to the enduring power that the book possesses. Even today when there are ever more journals, not to mention the whole range of electronic media, the science book has recently experienced a renaissance. If the history of the science book in the nineteenth century is anything to go by, such a development should by no means be found surprising.

Further reading

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Cahn, Michael (1991), *Der Druck des Wissens: Geschichte und Medium der wissenschaftlichen Publikation*, Berlin.

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Chapter Eight

Science Publishing in the Twentieth Century

A.J. Meadows

The expansion of science publishing

The most obvious problem facing the would-be reader of twentieth-century science publications is the vast amount of material to be covered as compared with earlier centuries. The main cause of this is the rapid increase in the number of scientists producing research round the world. Consider this first in terms of world population. In the seventeenth century, population growth was slow. The number of people in existence world-wide in the middle of the seventeenth century was perhaps about double what it was at the beginning of the Christian era. Since that time, and especially in the twentieth century, populations have grown much more rapidly. In 1950, the worldwide population was double what it had been in 1900. From this cause alone, a *pro rata* growth in number of scientists might be expected. But this is only part of the story. Educational standards have also improved rapidly worldwide over the past century (though obviously more rapidly in some countries than in others). For example, in the first half of the twentieth century, the number of people entering higher education in the USA doubled every 15 years: much more quickly than population growth. (The rate of increase in the UK was only slightly slower.) Taking this a stage further, it might be expected that the research-active population would be better measured in terms of doctorates awarded, rather than first degrees only. After the Second World War, interest in doctoral studies rose more rapidly in some countries even than growth in higher-education numbers as a whole. In the USA, for example, the number of doctoral students doubled between the

beginning and end of the 1960s. These rates of increase are a good deal shorter than the average lifetime of a scientist. It can be estimated that the number of qualified scientists who are alive today is more than the total number who are dead. Perhaps three-quarters of all the scientific researchers who have ever existed are around now.

Pinning down in detail what this expansion in the number of scientists means as far as publications are concerned is not easy. For example, many scientifically trained personnel nowadays are to be found in industry, where they are likely to produce no widely available publications. However, that there has been a general growth in the number of publications during the twentieth century is clearly evident. Table 1 shows the growth in book holdings of a sample of ten old-established American university libraries from the nineteenth century to the Second World War.[1] For comparison, Table 2 illustrates the growth in number of biomedical journal titles.[2] In looking at the figures for the latter, it is worth remembering the link to increasing readership. For example, the number of biomedical journals taken by the National Library of Medicine in the USA increased rapidly between 1960 and 1975. Yet, in terms of potential readership, the number of titles only rose from 15.5 per thousand members of the US medical community to 17.3 over this period owing to the concurrent growth in this community.[3]

Table 1. Book holdings of a sample of American university libraries

Year	1849	1900	1938
Average number of books held	28,779	187,082	1,182,974

Table 2. Number of biomedical journal titles

Year	1849	1900	1938
Number of journal titles	45	426	3937

An examination of the two tables suggests that the number of journal titles has grown more rapidly over the past century and a half than has the number of book titles of academic interest. The numerous studies that have looked at this question all confirm this conclusion. Even so, put in this way, the real difference tends to be under-emphasized. The amount of material contained in a scholarly monograph has not changed greatly during the twentieth century, whereas the contents of most scientific journals have expanded greatly. Individual journal

titles have had more issues – and, sometimes, volumes – produced per year; each issue may have been allotted more pages, and more words may have come to be crammed on each page. *The Journal of the Geological Society* in the UK – which can be taken as a typical example – increased in these various ways the amount of information it published per year by a factor of seven between the 1950s and the 1990s.

Another point can be made about the two tables. The expansion in the university library book holdings was for all subjects. More science books have certainly appeared in the twentieth century, but the figures are on a par with increases in the social sciences and humanities. Journal expansion has, on the contrary, been much more pronounced in science, medicine and technology than in other areas. (In the rest of this chapter, 'science' will be used as a shorthand for 'science, technology and medicine'.) What this reflects is something that was already becoming evident in the latter part of the nineteenth century. Important new results in science now first appear almost entirely in journals, whereas new research in other fields still often appears first in book form.

International science publishing

Launching successful new scientific journals has become an increasingly difficult and costly process. After the Second World War, partly for this reason, the publication of journals aimed at international readership became increasingly concentrated into relatively few countries. Table 3 lists the number of journal subscriptions placed by one American university library at the end of the 1980s;[4] the figures have been put in order of country of publication. The dominance of a few countries is evident. Indeed, put this way, the data disguise the concentration of journal publication into the hands of a few publishers. Thus most of the journals listed as coming from the Netherlands were actually published by Elsevier, and most of those from Germany were published by Springer.

As has been remarked, the overall growth in science publishing has reflected growth in the number of scientists. This does not necessarily hold for individual countries. Comparative data on journal authorship for the period round 1970

Table 3. Number of journal subscriptions placed by one American university library at the end of the 1980s

Country of publication	Number of journals subscribed to
USA	1105
UK	680
Netherlands	253
Germany	194

Table 4. A comparison of authors and journal title production

Country	Relative number of authors	Relative number of journal titles
USA	1.0	1.0
UK	0.25	0.79
USSR	0.20	0.33
West Germany	0.16	0.40

are presented in Table 4. These are compared with the relative data for the production of journal titles in the countries concerned. The Netherlands has relatively so few researchers that it does not appear in the table, even though Table 3 shows that the country produces large numbers of significant journals. The important factor here (as also, in part, for the UK) is the long and strong tradition of science publishing in the country. The interesting question, though, is raised by the position of the former Soviet Union. Table 4 shows it to have been strong both in authors and journal titles, yet it does not appear in Table 3. The problem was that Soviet journals were Russian-language publications, and few scientists elsewhere could read them. Attempts were made to overcome this in Western countries by, for example, producing cover-to-cover translations of important Russian journals. Even so, few Soviet journals counted as being truly international publications.

This point can be made in another way. It is possible to look at the references appended to the scientific papers published in one country and see which of them cite publications from another country. The results can be compared with the number of journal papers actually published in each country. When this is done for the USA, the Netherlands and the UK during the period of rapid growth in the 1960s and 1970s, it becomes apparent that journals from these countries received more than their fair share of foreign citations. West Germany and France received less than their fair share, while papers appearing in Soviet journals were greatly under-cited. These differences correspond well with other indicators of the amount of attention being paid to different countries' journal literature. It is supported, for example, by an examination of the extent to which foreign authors publish in other countries' journals. One study of chemical journals in the 1970s shows that 38 per cent of the authors in US journals were domiciled abroad, as compared with 3 per cent in West German journals and none at all in the Soviet journals.[5] The UK and the Netherlands proved to be special cases. In British chemical journals, 66 per cent of the authors were domiciled abroad (including 22 per cent in the USA), while for the Netherlands this figure rose to 93 per cent (including 25 per cent from the USA). The results reflect the major emphasis on international publishing in these two countries. Remembering the much higher level of journal title production in the USA, the data indicate that these three countries, all publishing in the English language,

are the ones that provide the important international mixing bowls for scientific research. These results for chemistry reflect, with greater or lesser variations, what happens in other scientific disciplines. For example, the geographical breakdown of sales of journals published by the Institute of Physics in the UK during the 1970s was: UK – 13 per cent; Western Europe – 14 per cent; Eastern Europe – 10 per cent; North America – 35 per cent; Japan – 9 per cent; rest of the world – 19 per cent.

The question of the language to be used in scientific journal publications has undergone some change with time over the past century. In the nineteenth century, German was the commonest scientific language, though French continued to rank as highly important. (Russian scientific authors still often wrote in French in the early twentieth century.) Throughout the twentieth century, English has become increasingly important as a language of science: after the Second World War, it came to dominate the contents of journals aimed at an international readership. Scientific journals published in the Netherlands are now almost entirely in English, and it is commonplace even in French and German journals. Papers produced in such countries as Japan, where scientific research is expanding rapidly, are also typically presented in English for an international audience. The same changes can be seen in the production of abstracts and abstracts journals. In the nineteenth century, the leader for this activity was Germany, followed by France, the UK and the USA in that order. The USA moved into second place after the First World War; then took over the running from Germany after the Second World War. Correspondingly, the language of abstracts came increasingly to be English.

Disseminating scientific research

Mention of abstracts raises the question of the various aids to information retrieval and dissemination that have been developed over the past century. Abstracts journals provide condensed versions of the papers that appear in the (full-text) research journals. They were created in the nineteenth century as the growth in number of journals began to make keeping up with the literature increasingly difficult. As the number of different research journals has increased, so, naturally, has the number of abstracts journals covering them. Alongside these, different kinds of indexes have been developed as a guide to the journal literature. One example is the keyword-in-context (KWIC) index. In such an index, the keywords in the title of each journal paper are selected, and presented in alphabetical sequence, with the rest of the title laid out on each side of the keyword. This gives the reader several chances of picking up relevant papers. Another example of a reader aid is *Current Contents*, which reprints the contents pages of recent journal issues in particular disciplines. This allows readers an opportunity both to scan a wide range of current journals quickly, and to identify potentially relevant articles in journals to which they do not have

immediate access. One other aid, devised after the Second World War, was the citation index. In the guise of the *Science Citation Index* (published in the USA) this allows a reader who is interested in a particular paper to see which other authors have been citing it.

Along with these aids for identifying relevant journal literature, dissemination devices based on the author's own initiative have become commonplace. The older of these is the offprint (a copy of a paper that is distributed by an author after the original has appeared in a journal). These were formerly called 'reprints', because, with the printing processes in use earlier in the century, papers actually were set up and reprinted; now they are printed off along with the journal itself. The growth of photocopying has made offprints less important, but they still have value for papers with many photographic illustrations. They are also still in request from countries, especially developing countries, where the original journals are difficult to access.

The more recent author dissemination device – it has only really become popular since the Second World War – is the preprint. In this case, copies of a paper are circulated to colleagues prior to its appearance in a journal. Originally, this was only done after the paper had been accepted for publication, but, more recently, preprints have been circulated before they have been subject to external quality control. The motive either way is to try and speed up the dissemination of new results. A scientific journal may take (say) six months from receipt of a paper to its appearance in print. In a fast-moving research area, this is a long time to wait for information. Both individuals and libraries in the past have made collections of reprints. With the advent of electronic communication – as will be explained later in this chapter – access to preprint collections has become both easier and increasingly popular.

The existence of journals which are cover-to-cover translations of other journals has been mentioned above, as has abstracts journals. These are both examples of specific types of journal, but they are not the only ones. Letters journals were introduced for the same reason as preprints – to speed up the dissemination of research information. Since they are properly refereed journals, they take longer to appear than preprints, but the delay is appreciably less than for mainline journals in the field. The original idea was that letters journals – as the name implies – should contain brief communications, which could be amplified later into full-length papers in ordinary journals. In practice, though, this does not happen: contributions to letters journals often represent the main announcement of the research, rather than a preliminary statement. Another type of journal, the review journal, was introduced as a further aid to researchers. Review journals systematically and (usually) critically discuss the literature that has accumulated on a given research topic over a specified period of time. They provide an entry to the topic for newcomers to the field, and a check on important publications for experienced researchers in the field. Collected reviews are often published annually, perhaps in volumes entitled 'Advances in ... '. These typically appear hard-bound like books. Conference proceedings, a

characteristic publication of the second half of the twentieth century, lie somewhere between a journal and a book. Like reviews, they may appear as part of a journal, or as a separate book. It is usual to distinguish between refereed and unrefereed proceedings. The former are more akin to reprints and the latter to preprints in terms of their use as information sources.

Journal publishing

The definition of what constitutes a 'journal' is far from clear-cut. In the latter years of the twentieth century, an increasing number of newsletters devoted to science and technology has appeared. As their name implies, newsletters are particularly concerned with reporting events and personalia, but they often also summarize important research findings and papers given at conferences, and, to that extent, overlap with journals. Again, there are semi-popular magazines, such as *New Scientist* or *Scientific American*, that are read by researchers in all disciplines who find them a useful way of keeping up with developments in other disciplines; thus they supplement normal journal publications. Nor are journals restricted to paper as their only medium for production. Microform (a word that covers both microfiche and microfilm) has been used for journal production for many years. The difference from print-on-paper journals is that microform has mainly been for archival storage, rather than current reading. The same is true of a newer medium, CD-ROM, although not of online electronic journals (both of which will be discussed later).

Specialization

Along with a proliferation in the number and types of journals, there have also been considerable changes in the contents of journals. The problem for scientists has obviously been – how can they keep up with the ever-increasing flood of publications? The answer for a long time has been that they do not even try to do so. Instead, they select a limited range of topics, for which the amount of information is sufficient for them to absorb. Such specialization has been going on for many years, as can be seen by looking at the careers of scientists over the past three centuries. The founders of the Royal Society in the seventeenth century were expected to be interested in any branch of science. By the early nineteenth century, scientists such as Davy and Faraday concentrated almost entirely on the physical sciences. At the beginning of the twentieth century, their successors were fairly well differentiated into physicists or chemists. During the twentieth century, more and more specialist topics have appeared and grown. For example, some physicists in the latter part of the century call themselves 'condensed matter' physicists, and might now, indeed, claim to be a researcher in a specific area of condensed matter physics.

Journals have naturally tended to follow the same path, otherwise their contents would become too diffuse to attract an adequate readership. The trend towards specialization can be seen, to some extent, from the way titles of journals have changed as time has passed. The newer titles typically reflect a narrower coverage as compared with the older ones. In fact, the contents of the latter have often become more specialized with time, even though the title has remained the same. For example, the *Philosophical Magazine* was founded in London at the end of the eighteenth century with a wide brief as regards its coverage. By the end of the nineteenth century, it had come to be recognized as primarily a journal for papers on physics. After the Second World War, it was decided to concentrate more specifically on the physics of condensed matter. Subsequently, the journal was split into separately published sections which dealt with different specialities within the physics of condensed matter. The title throughout has remained the *Philosophical Magazine*.

Specialization has not only affected where scientific information appears: it has also affected how that information is generated. Much scientific research nowadays entails team work between specialists, typically including colleagues, research students and technicians. In extreme cases – as can occur in a high-energy physics experiment – a hundred or more people may be involved. Each person contributes to a particular aspect of the experiment: few have a detailed overview of the entire project. This collaborative activity is reflected in the papers that report the research, more especially by the appearance of multi-author papers. A few papers have had so many contributors that they have appeared in journals attributed to an institution, rather than to a set of individuals. Even so, not everyone who contributes to an experiment is necessarily included as an author. Technicians, for example, are typically excluded.

As would be expected, growing specialization during the twentieth century has been matched by increases in the proportion of multi-authored papers. In physics, for example, the proportion of multi-authored papers appearing in journals increased from some 25 per cent in the 1920s to over 60 per cent in the 1950s, and has continued to increase since. The use of complex (and highly expensive) equipment – 'big science', as it has come to be called – almost invariably involves collaboration. Workers in 'little science' are usually under less pressure to collaborate, unless the work entails input from different specialists. As Table 5 indicates, the various needs of research are such that, even in little science, the trend towards collaboration is still apparent.[6] For example, the proportion of multi-authored papers in psychology increased from 15 per cent in the 1920s to some 45 per cent in the 1950s.

The growing specialization and complexity of science has required corresponding changes in the education of people who hope to undertake scientific research. Their training has become both more intensive and more theory-based. The effect of this has been increasingly to create a distinction between professional scientists and others, a distinction that has naturally been reflected in the literature. Nowadays, it makes sense to distinguish three groups who are

Table 5. Multiple authorship in different subject areas

Subject	Percentage of multi-authored papers
Chemistry	83
Biology	70
Physics	67
Psychology	47
Mathematics	15

consumers of literature about science – professional scientists, amateurs and the general public.

Sciences can be roughly divided into two kinds – the experimental and the observational. The former includes most of such subjects as physics, chemistry and the biomedical sciences, which nowadays require expensive equipment and complex techniques, both centred on a laboratory. The latter category includes those parts of such subjects as astronomy, meteorology, geology and biology which depend on direct observation of the environment, where some observations can be made at relatively low cost. Moreover, such observations often require relatively little theoretical knowledge. Consequently, amateur scientists tend to congregate in these subject areas, which are also often of particular interest to the general public.

Until the latter part of the nineteenth century, the distinction between professionals and amateurs was not of overwhelming importance. In the nineteenth century, the two could usually cohabit happily within the same learned society. This is still true of such amateur-dominated topics as ornithology, but, for the most part, the twentieth century has seen a change. Though there are still societies where professionals and amateurs can mingle, there are also now a number of disciplines in which separate professional and amateur societies exist and produce their own publications. This is at the national level. Most professional societies now operate primarily at this level, though they may contain regional groupings. Similarly, their publications typically cater for their entire national membership. Many amateur societies, on the contrary, operate at local or regional level, and, correspondingly, produce regionally based publications. These often contain useful information about the locality, but may be difficult for potential readers outside the region to trace and acquire.

Society and commercial publishers

In the first half of the twentieth century, learned and professional societies were the dominant publishers of scientific journals, although some well-established commercial ventures existed (such as *Nature*, published by Macmillan, which

celebrated 50 years of existence shortly after the end of the First World War). The audience for scientific research papers was then fairly small; sales were limited and not such as to attract great attention from many commercial publishers. The societies were in a different position. The journals were provided as part of their services to members, and the financial backing for them was taken out of members' subscriptions. Journals were acquired primarily by individuals, who relied a good deal on their own collections of materials for information.

All this changed rapidly after the Second World War. In the Western world as a whole, university departments began to grow rapidly, while government and industrial research also expanded greatly. The result was both more research, and a much larger audience for publications describing the research. Commercial publishers spotted the new opportunities that these developments offered, and moved increasingly into the field of publishing both science journals and science monographs. A count of the number of scientific journals launched by three major US publishers during the period 1945–60 shows an increase from zero to twenty in the decade 1945–55. This was followed by an even more rapid expansion to 55 titles by the end of the 1950s. The most obvious example of this new commercial interest was Pergamon Press. Starting from scratch in the UK at the beginning of the 1950s, it became one of the major producers of specialist scientific journals over the next two decades.

One result of this expansion was that individuals could no longer afford to purchase all of even the key journals they required. Journal purchasing therefore became increasingly the responsibility of institutional libraries. The transition from personal to institutional subscriptions was encouraged by the escalating prices of journals. This was only partially offset by the growth of a two-tier pricing system, whereby individuals paid much lower annual subscriptions for a journal than institutions. Correspondingly, learned societies began to make the purchase of their journals a separate, voluntary activity, rather than an integral part of the members' subscriptions. For example, over the period 1953–64, the number of Fellows of the Chemical Society in the UK who personally subscribed to the Society's journal decreased by 80 per cent. At the same time, the number of copies sold to libraries in the UK rose by nearly 90 per cent.[7]

The success of commercial journals soon began to have an impact on the way society journals were produced and marketed. For example, many society journals had kept a very traditional appearance. The new commercial journals adopted much more contemporary designs, and slowly (and often reluctantly) the societies began to follow their example. The growth of the commercial journals related, in part, to the appearance of new specialities, for which the societies were not catering adequately. The societies therefore began to look again at their own journals, in some cases splitting their existing, fairly generalist journals into a number of more specialist publications. Nevertheless, societies retained some in-built advantages over commercial publishers. Their journals were usually well established and highly regarded by authors and readers. In addition, they could readily call on the goodwill of their members to act as

editors and referees. From the viewpoint of purchasers, society journals – when costed per page – continued to be better bargains than the average commercial title (see Table 6).[8]

Table 6. Average cost (cents per page) for different publishers

Type of publisher	1973	1985	Increase
Commercial publisher	3.7–4.0	19.3	400%
Society publisher	2.9–3.2	10.4	240%

Developments in the latter half of the twentieth century have actually led to a notable convergence between society and commercial publishers. This is not only a matter of physical appearance, or of a need to cater for new specialities. As their publishing operations expanded, many societies found they were no longer able to handle their publications on the basis of voluntary or in-house expertise. Consequently, many journals are now published via some kind of co-operation between societies and commercial publishers.

Discussions of science journals in the latter part of the twentieth century came increasingly to be dominated by the question of journal prices. Complaints about the high prices of journals are far from new. Before the First World War, scientists were grumbling about new journals produced by commercial publishers, whose prices were so high that only libraries could afford to subscribe. The real debate about the problem was, however, delayed until more recent decades. It has arisen from two main causes – the greatly increased number of journal titles and the rate of increase of journal prices. The latter point is illustrated in Table 7 by data on average price increases for a selected set of journals.[9]

These increases are appreciably larger than general price increases for retail items over this period. Indeed, Table 7 conceals the point that the journals with the highest prestige – those most in demand among scientists – tend to have increased in price more rapidly than the average. Since individuals can only

Table 7. Journal average price increases

Year	Average subscription cost ($)	Index
1977	51	100
1980	73	143
1983	113	220
1986	152	296
1989	199	388

subscribe to a small fraction of the titles now appearing, the main burden of purchasing these journals falls on libraries. Library budgets in most countries were not expanding much in real terms by the 1990s. The rapid growth in journal subscription prices therefore meant than an increasing fraction of the library budget devoted to the acquisition of materials was being spent on journals. The purchase of books was correspondingly restricted. In the period 1973–87, funding support for the leading research libraries in the United States rose by 234 per cent (compared with a rise of 183 per cent in the US Consumer Price Index). The average expenditure on stock grew in response, but it involved a shift in the amount expended on journals from 40 per cent to 56 per cent of the total acquisitions budget. During the same period, the number of journal titles held by the average research library fell appreciably, as price increases reduced the number that could be afforded. Inevitably, there have been acrimonious debates between librarians and publishers concerning the reasons for journal price inflation. The important point, though, is that the process whereby publishers produce ever more and larger journals, which purchasers are increasingly unable to afford, cannot continue for more than a limited period of time. In the last quarter of the twentieth century, the strains involved have become evident. The number of new journal titles appearing began to slow down, but, even so, the number of subscriptions to each title fell continuously. That so many journals continued to be financially viable can be attributed, in part, to the increasingly efficient means for producing and handling printed material. But clearly, unless the number of scientists and the size of their budgets begin to grow again, either journals must evolve towards a steady state, or some substitute must be found for them.

This problem has confronted science (including technology and medicine) more than other areas of research. The expensive journal titles are mainly in science, as are the costly abstracts journals; it is science that has changed the traditional purchasing balance of libraries. Science has also created a possible avenue via which some alleviation of the problems might be found – the application of electronic publishing.

Electronic publishing

From the early years of modern science in the seventeenth century, paper has provided the material basis for the dissemination of research results. After the Second World War, electronic computers developed rapidly. It was evident from the start that they could be used to handle text, as well as numbers. Handling text held its own complications, but they began to be disentangled in the 1960s. The ability of computers to deal with small chunks of text efficiently was then applied to handling the abstracts of papers in journals. Electronic databases of journal abstracts had the advantage that large amounts of information could be stored and searched much more readily that way than as print-on-paper. Over

the remaining years of the twentieth century, usage of abstracts moved increasingly from paper-based publication to electronic versions. In this, abstracts paralleled other secondary publications, including various types of index, which also moved from print-on-paper to electronic form.

Handling of full-text material, such as constitutes journal papers, became reasonably straightforward by the 1990s, and even graphics handling, though sometimes requiring an inordinate amount of time, became easier. Initially, less formal text items received most attention. Electronic mail became common in research circles. During the 1990s, a majority of scientists came to have some acquaintance with it. Electronic newsletters and related types of communication appeared with increasing frequency in the early 1990s. By the middle of the decade, conditions were becoming suitable for the support of sizable numbers of electronic journals (usually taken to mean an electronic publication made up of one or more refereed papers which report original research). The basic requirement for reading all such forms of electronic publication is the same – ready access to a computer attached to a network.

If it took some time to get computers to handle text in a way acceptable to readers, it also took time to establish electronic networks which could be used to distribute the text. Initially, electronic networks linked mainframes employed mainly for number-crunching by scientific researchers. Thus, NSFNet in the USA linked together institutions involved in research funded by the National Science Foundation, while JANET (the Joint Academic Network) in the UK was originally set up to link university science departments and other research centres. Though intended primarily for transmitting numerical data, these networks soon proved useful for distributing text. The appearance of microcomputers in the 1980s led to these wide area networks (WANs), as they were called, being connected to local area networks (LANs) of microcomputers – for example, linking individual researchers on a university campus. This encouraged still further the distribution of text, to the extent that, by the mid-1990s, text and graphics had become more important than numerical data in the planning of networks. The logical outcome of these developments was the Internet, which effectively distributed any sort of information to any sort of person.

Electronic journals are still suffering from teething problems, and, in any case, not everyone yet has immediate access to a network. These problems can be circumvented by storing a journal electronically on a medium that can be physically distributed in the same way as a printed journal. The favourite that developed in the 1990s is CD-ROM (compact disk read-only memory), so called because users can only read the information on the disk: they cannot change it. Compact disks are not ideal for information-handling purposes, but they are relatively cheap to use as a storage medium because of their popularity for purveying music. As a way of providing journal papers, such disks present a problem: they have much more capacity than is required for storing a single issue of the average journal. The CD-ROM is therefore a very wasteful way of providing a substitute for an issue of a printed journal. What it does provide is a

good method either for storing successive issues of a journal over an extended period of time, or for storing simultaneously the current issues of a number of different journals. The capabilities of compact disks have been undergoing continuing development. New versions are becoming capable of handling multimedia information (combining text, sound, still and moving pictures), so opening up new possibilities for electronic publishing of research information.

For providing current issues of journals, online dissemination is certainly a better bet than CD-ROM. In terms of future developments, it offers more flexibility than print-on-paper. The almost universal introduction of hypertext for electronic journals has enhanced this flexibility, though sometimes also increasing the difficulty of navigating through the journal on-screen. Not only can information be disseminated more rapidly via electronic networks, it can be done at any time, and author–reader interaction is easy. Indeed, the interesting question at the end of the twentieth century is what role publishers and libraries should come to play in the distribution process. There is, in principle, nothing to stop authors from inputting their own papers to a network and distributing them directly to potential readers. In practice, electronic journal publishing is not always that straightforward. There is first the question of cost. Early electronic journals were typically started by one or more enthusiasts, who donated time and effort to the production of the journal. As a result of their enthusiasm, these journals have usually been made available without subscription.

Such a reliance on voluntary labour is acceptable so long as the scale of operations remains small and the contents are straightforward to handle. In other words, it works for small-scale publications. Many scientific journals are not of this type. They not only contain large amounts of material, but also have to handle a complex mix of contents (equations, graphics, etc.). This requires expenditure on well-trained staff along with all the associated overheads. To balance this, readers must pay to access the journal. If the payments are at all sizable, this will involve the library, rather than the individual reader. Equally, the way complicated electronic journals work is not necessarily immediately obvious to readers, who will need assistance from librarians. The implications of this are that major scientific journals will, for the immediate future, be handled by both publishers and libraries, as printed journals have been.

Even given assistance, many readers continue to encounter difficulties in using electronic journals. Reading successfully online requires more things to be right than reading a printed journal. Not only must the network link be running smoothly: it must also have the capacity to deal speedily with the flow of information. Different types of information, which are equivalent for printed matter (for example, text and colour photographs), can take considerably different times to handle electronically. Readers expect to be able to scan rapidly backwards and forwards between text and graphics, and object to any electronically imposed delay. There is the further problem that the actual on-screen appearance of the journal can depend on the particular hardware/software configuration used by the reader. Again, there have been well-aired criticisms

concerning the portability of electronic journals. A printed journal can be carried and read anywhere, whether at work, home, or travelling. Such portability is considerably more difficult for electronic journals.

To the extent that the problems are technological, solutions can be found. Libraries can cache frequently used material – such as current issues of electronic journals – locally, so that their readers can retrieve them quickly. Similarly, individuals can download selected papers onto portable computers. To set against the difficulties, computer handling of scientific papers can offer potential advantages over printed matter. These range from the ease of electronic searching for specific information across a range of papers or journals, to the ability of authors to include much more detail about their work owing to the far greater storage capacity of electronic as compared with print media. The question is, how long will it take before the advantages of electronic publishing win out over current defects? There is a fundamental point at issue here. Science and paper-based communication have evolved hand-in-hand. The structure of the scientific communication system has been partially shaped by the properties of print-on-paper. A move to electronic publishing therefore involves more than simply a move from one communication medium to another: it can imply basic changes in the way scientists communicate. The current best guess is that electronic journals will dominate printed journals by 2010. If so, the end of the twentieth century marks a crucial watershed in the development of scientific communication.

From the publishers' viewpoint, this transition period is central. When, and under what circumstances, will readers prefer electronic to printed journals? If they are to remain financially viable, publishers must make the transition at just the right time. Their response has naturally been to produce parallel electronic and printed versions, and to try and devise a joint costing mechanism that will protect their income. (This approach has worked quite well for secondary publications, such as abstracts journals, which started the transition earlier.) The question of how much electronic journals cost to produce has been a major debating point during the 1990s. Many researchers argue that electronic production and dissemination is intrinsically cheaper than for the print equivalents. Hence, the prices of journals should fall as they go electronic, so helping alleviate the problem of limited library budgets. However, many publishers dispute that electronic handling of journals offers major cost savings.

The existence of both electronic and printed versions of journals also overcomes, for the time being, a major query concerning electronic journals – how and by whom back issues should be stored. Handling the long-term storage of electronic journals is not something that attracts either publishers or librarians. The basic difficulty is that methods of gaining access to electronic information are continually changing. Anyone who stores such information must therefore be prepared to upgrade hardware/software regularly to correspond to the new standards. The task might best be offloaded on central depositories, such as the national libraries, but the details of such an arrangement remain to be worked

out both nationally and internationally. The continuing production of parallel printed versions at least provides time for discussions to take place. For some purely electronic journals, the question is already beginning to press. Interestingly, microform is proving useful as a temporary storage medium, since information in this form is subsequently fairly easy to digitize.

One of the significant ways in which electronic publishing differs from print-on-paper publishing is in its ability to blur some of the clear-cut distinctions that exist for printed publications. For example, there are major differences between a personal letter and a journal as a method of communicating scientific information. With electronic mail, the differences become less evident. A personal letter can readily be made to look like a paper in electronic format, and it can be disseminated widely just as readily as an electronic journal. This blurring of categories is one reason why a transition to predominantly electronic communication raises queries about the way the scientific community operates. For example, physicists have always been concerned with the rapid dissemination of new results. Hardly surprisingly, they grasped the opportunities offered by networking to provide central files of physics preprints. These have become very popular, and the idea is spreading to other subjects. Unlike the paper-based world, where journals and preprints are evidently different, the only important difference between an electronic preprint file and an electronic journal is that papers in the former have not been refereed. In a similar way, the differences between journals, conference proceedings and books can be a good deal less apparent for electronic than for printed versions.

The major problem with extended pieces of electronic texts, such as books, is reading them. Scanning a computer screen for a long time is typically more tiring than reading the same amount of text in printed form. In any case, most computer screens hold much less information than a printed page. Nevertheless, scientific books, including various classics in the history of science, have been made available online, though readers may prefer to print them out rather than read them on-screen. More recently, hand-held electronic books have been developed. Material can be downloaded – in some cases, several different book titles simultaneously – and replaced as desired. As with electronic journals, electronic books can offer some advantages over the printed versions. For example, the electronic text can be searched for specific items of information much more efficiently than is possible with the printed text.

Science books

The main emphasis so far has been on journals, because they undoubtedly became the dominant source of scientific information in the twentieth century. By the middle of the century, books only functioned as primary sources of information for a minority of scientists. In such sciences as physics and chemistry, books figured as one in ten of the sources cited (rising to one in five for

mathematics). References to journals increasingly dominated throughout the century. Despite this, books still play an important role in science. The continuing need for teaching material to train the growing number of scientists, combined with the continually changing extent of scientific knowledge, means that textbooks have not only grown in number during the twentieth century, but have also required fairly frequent updating or replacement. In addition, scientists themselves have increasingly required good reviews which explore specific research topics in depth. In consequence, scientific monographs have continued to be important throughout the century.

Scientific reports, in one form or another, go back to the early days of science. However, they have proliferated in the twentieth century, not least as a required spin-off from government or commercially funded research projects. They often contain information not available via other sources, but they can be difficult to track down. Patents, another growth area from the previous century, are better organized, even though their numbers have escalated in parallel with those of other scientific publications. Both reports and patents are valuable for providing insight into government and commercial scientific research, whereas journals and books more often reflect academic research. In a rather different, and much older, category, maps and map-making have expanded greatly during the past century. As a way of summarizing data – for example, the distribution of fauna and flora – a diversity of forms of presentation have been devised. At the same time, totally new maps – for example, of the ocean floors, or planetary surfaces – have been produced, especially after the mid-century. With the development of GIS (geographic information systems), maps and mapping have become computer-based. As the century ends, printed maps have effectively become subservient to the digital versions.

The number of science books in production worldwide has grown greatly since the early years of the twentieth century, though the figures have been less startling and more variable than those for journals. For example, the number of science titles being published each year in the UK grew rapidly from the 1980s into the 1990s, but actually fell during the 1970s. As with journals, the growing dominance of the English language is reflected in the publication of science books. The emphasis is, however, less pronounced. At the research level, English-language texts are used in a number of countries where English is not the first language, but translations are commoner for books than for journals.

Table 8 provides a rough estimate of the relative production of monographs by four leading countries in the 1970s. The order is compared with the relative figures for the production of journals (taken from Table 4). It is clear that the production of monographs is considerably less concentrated into a few countries than journal production.

In terms of price increases, science monographs have again differed from journals. For example, the average price of a science monograph published in the UK rose from £2.65 in 1964–65 to £6.29 ten years later. However, when this increase is compared with the Retail Price Index, it appears that the real

Table 8. Relative production rates for monograph and journals

Country	Relative number of monographs produced	Relative number of journals produced
USA	1.0	1.0
UK	0.42	0.79
USSR	0.96	0.33
West Germany	0.54	0.40

cost of scientific monographs actually decreased over the period. Certainly, science monographs have not escalated in price to a greater extent than monographs in a range of other disciplines.

One result of specialization is that science books have become more highly differentiated during the twentieth century. Only specialists are likely to read research monograph or journals today. The problem for other readers is both their lack of the necessary conceptual background and the difficulties they encounter in coping with the style. At the beginning of the century, scientific language certainly contained some specialist vocabulary, but it was, for the most part, not too far removed in presentation from the general reading matter of educated people. As the century progressed, the proportion of specialist, concept-laden words in the text increased, and the style also changed. Scientific writing came to be increasingly both highly impersonal and highly structured. For the cognoscenti, this made the retrieval of information easier; for the average reader, it made it much harder.

Books trying to explain science to a popular audience are not new: they have been necessary ever since many of Newton's contemporaries found that they could not understand the *Principia*. In the twentieth century, however, the range of scientific topics to be covered has grown rapidly, and the didactic quality that had previously been evident in many of these works declined. Moreover, there were developments in who wrote such books. As science has become increasingly the activity of professionals, so the scientific community has become increasingly dubious whether its members should spend time writing specifically for a general audience. This has not prevented a number of scientists, including some of the most eminent, from doing so. One famous example is the (almost competing) popular science books written by two of the leading British astronomers, Eddington and Jeans, in the 1930s. It was only towards the end of the century that the scientific community in Western countries began actively to encourage its members to write books of popular interest. Popular science writings by amateurs have not come under this prohibition, and have occurred throughout the century.

Meanwhile, the growth of the mass media has encouraged the appearance of a new kind of specialist – the science journalist. Though some already existed

prior to the Second World War, it was the post-war expansion of science that really established their role. Thus the National Association of Science Writers was set up in the United States in 1934. By the outbreak of the Second World War, its membership was only about 20. By the early 1960s, this had expanded to some 200 members. Similar developments occurred in other countries: in Marxist-led states, the need to popularize science formed part of the prevailing ideology. In the latter half of the twentieth century, presentation of science via television has had most impact on members of the general public; but surveys have shown that books and magazines have continued to be important sources of information on science for them. In fact, as television 'tie-ins' show, popular science books and related television programmes can supplement each other successfully.

Science magazines have had their ups and downs during the twentieth century. Many of them have had relatively short lifetimes. The most successful ones seem to be those that have been used for general reading by professional scientists, as well as attracting a non-professional readership. Semi-popular technology magazines have, perhaps, been more successful overall than magazines devoted to pure science. The obvious example is the plethora of popular computer magazines in the last decades of the century. Worth a passing mention, too, is science fiction. Like popular science, this proliferated in book and magazine form during the century. The heyday for emphasizing the scientific aspects in such stories was probably in the period after the Second World War, but science fiction is still capable of stimulating an interest in scientific ideas today.

Publishing changes

These different sorts of science publications have been produced by a variety of publishers. University presses were leading publishers of scientific monographs in the first half of the century. In the latter part of the century, the commercial publishers greatly expanded their role in producing such books. University presses have also been significant producers of popular science books, but commercial publishers have equally been involved throughout the century. Popular science magazines (and science fiction) were dominated by commercial publishers from the start.

Twentieth-century science publications have come to be considerably more varied in appearance than their equivalents in previous centuries. In part, this is because of greater experimentation in design, but it is even more due to technical developments during the century. In the first half of the twentieth century, methods of printing followed mainly the lines laid down during the nineteenth century. However, new methods were being developed during those years which came to dominate printing activities in the leading publishing nations after the mid-century. At their basis lay a combination of photographic lithography with

offset printing. What this meant essentially was that text and graphics in photographic form were reproduced as an image on a metal plate (this being 'photographic lithography'). The image was not printed directly on to paper, but transferred via an intermediate surface (hence 'offset'). This new process had a number of advantages, especially increased speed, consistency and the ability to handle all kinds of graphics. For example, papers in biology journals could readily be printed with colour photographs interspersed throughout the text.

Another significant post-war development was the growth of phototypesetting. In this, text characters are created in photographic form from the start, so the process complements the use of photographic lithography. The important aspect of this development is that the production of the characters can be controlled by a computer. This has led in the latter years of the twentieth century to the rapid growth of computer-assisted typesetting. Such typesetting has fitted in well with the increasing use of computers by publishers for editing, since the material to be printed can be exchanged between publishers and printers in digital form. This, in turn, has fitted in with the growing ability of scientific authors to provide their texts in digital form. In principle, only the final stage of the production process, when the book or journal is printed, requires transfer to paper: all the other steps in the publishing chain have become computerized. In consequence, the move to fully electronic publishing – as with electronic journals – has, technically, become relatively straightforward.

Technical innovation has also made it much easier for publications to be copied. In science, authors have typically retained their copyright in books, though publishers have increasingly claimed it in journal papers. In either case, publishers have been greatly worried by the extent to which copying may occur. Pirated science books have not been uncommon, especially in Asia. Copying of journal papers has been a more debatable topic, since some copying for research purposes is allowed in many countries. For some years, the process at the centre of these debates was photocopying, involving a transfer of image from the original work to specially prepared paper. As a form of printing, the process has been used by the publishers themselves to produce books, especially facsimile copies of existing publications. It has proved a useful way of producing short runs of books or journals, particularly since good colour photocopying has become available. The publishers' worry is that almost anyone can reproduce copies in any required quantity, for photocopiers are so widespread nowadays that full control of their use is virtually impossible. The move to electronic publishing in the 1990s has only served to enhance these fears, since manipulating and copying material in electronic form is even easier and less controllable than photocopying. The impact of all this technical development has led a number of countries to introduce new and more comprehensive laws regarding intellectual property rights.

Publishing worldwide

Most of the discussion in this chapter has centred on the major science publishing countries. For the nineteenth century, this is obviously appropriate; it is less clearly so for the twentieth century, since science is now recognized worldwide as being of fundamental importance. Countries which concerned themselves with the development of science long since – Australia and Japan are, in their different ways, examples – have followed rather similar paths in terms of scientific communication to Western Europe and North America. Developing countries outside this magic circle have found it difficult to establish their scientific base. For example, in the latter part of the 1960s, well over 50,000 scientific authors were recorded as living in the United States. In comparison, the whole of Latin America had slightly more than a thousand authors, and the whole of Africa considerably less than a thousand. Another way of looking at this is provided in Table 9 which ranks countries in order of the number of papers in scientific journals they produced early in the 1990s.[10] The growing strength of Japan is well illustrated, but the interesting point is the appearance of India in the list.

India is a typical developing country in the sense that the proportion of scientists to the entire population is small. However, because the population is large, scientific research occurs on a significant scale. In terms of disseminating this research, India faces a dilemma: should the necessary monographs and journals be produced in India, or should the work be published abroad? The first alternative might seem obviously preferable. Apart from other considerations, the amount of money available for purchase of foreign scientific journals has always been limited. The number of such journals purchased by Indian

Table 9. Number of journal papers produced per year by different countries

Country	Number of papers
USA	112,955
UK	52,150
Japan	44,521
Germany	40,378
USSR (former)	32,838
France	30,102
Canada	27,181
Italy	17,803
Netherlands	12,699
Australia	12,592
India	10,468
Sweden	10,125

libraries dropped between the mid-1980s and the mid-1990s by a third. Hence, it makes financial sense to concentrate on publishing within the country. The problem is that purely Indian publications tend not to be greatly read abroad. From the viewpoint of Indian scientists, this means that publication in Indian journals is unlikely to attract international attention, whereas publication in journals from the leading science nations may. The overall result is that Indian science publishing is gradually expanding, but it is held back by the fact that some of the best work is published abroad.

The question of size of the scientific community is often crucial. Australia stands just above India in Table 9. Its per capita proportion of scientists is much greater, but the total numbers of scientific authors are somewhat similar in the two countries. Consequently, it suffers from the same publishing dilemma as India. At least, these two countries are less troubled by language problems. The leading Indian publications are mainly in English, for there is no agreed national language. The data in Table 9 are based on papers in journals which receive some kind of recognition beyond their country of origin. This implies a built-in bias in favour of languages that are widely used for the international communication of science. A developing country, such as Brazil, which has some similarity in research terms to India, is therefore further disadvantaged if it publishes in its national language – in this case, Portuguese – since that is not widely read. The extreme example of this is China, which does not appear in Table 9. There is a great deal of scientific publication there, but most of it is unknown to the outside world because it is in Chinese. The move to electronic publishing is only serving to emphasize this language problem, since the vast majority of scientific material currently available in electronic form is in English.

One area of science publishing that has grown greatly in the past century is that stemming from international bodies. Such organizations as UNESCO, or the European Union, produce a range of scientific or technical reports that are typically made available in a number of different languages. Equally, the various international scientific unions that have been created during the twentieth century have encouraged international co-operation in terms of making scientific information available. Some international bodies – such as CODATA (the Committee on Data for Science and Technology) – were set up specifically to promote international discussion of information. They supplement, to some extent, the range of international encyclopaedias, or Handbücher, which have appeared throughout the twentieth century, based on the German tradition of the nineteenth century.

Science libraries

Despite the growth in the amount and diversity of published scientific information, the actual types of institution that house important collections of scientific material have not changed greatly since the nineteenth century. The major

universities that existed then continue today, though some have been split to form more than one institution. Correspondingly, their library collections have expanded very greatly. At the same time, large numbers of new universities have been created worldwide, especially in the second half of the century, and have built up their own library collections. (In passing, it might be noted that some of these newer universities have acquired collections relating to past science, or scientists, of historical significance.) As part of setting up their collections, these newly created universities have been in the market not only for out-of-print monographs, but, more particularly, for back-runs of journals. In the last years of the twentieth century, universities in many countries have been subject to increasing financial stringency, which has considerably affected such purchases. In the heyday of universities, especially in the period around the 1960s, there was such a demand for journal back-runs that it proved worthwhile to produce facsimile and microform copies. The overall result of the century's growth is that university libraries now represent in many countries the single largest institutional information source for scientists.

The libraries of learned and professional societies have become less central to scientists than they were in the nineteenth century. Most society members prefer to obtain their information from their local institutional library, backed by their personal library. They therefore no longer consider it essential for societies to maintain comprehensive, up-to-date libraries. In consequence, such libraries are tending to become places for studying the history and development of a subject, rather than to advance its current state. Much the same can be said of museum libraries, though here it depends considerably on the subjects covered by the museum. In general, museums covering the experimental sciences, medicine and technology have libraries that are primarily useful for studying the history of the subject. Museums dealing with such subjects as geology, botany or zoology may have active researchers on their staff and will therefore try to cater for both past and present.

Even national libraries have suffered from the great expansion of scientific literature during the twentieth century. Sooner or later, their budgets have simply not grown fast enough to maintain a comprehensive coverage. Compulsory deposit requirements have helped those national libraries situated in countries with major science publishing programmes, but have not changed the overall picture. During the century, national libraries have increasingly been seen as libraries of 'last resort' (that is, where readers go to consult publications that they cannot find elsewhere). Even in major science publishing countries, meeting this expectation has become difficult. One consequence of the growing problems of adequately covering international science literature has been the development of inter-library loan schemes. These provide readers either directly with the required items, or indirectly via photocopies. Such schemes typically place considerable reliance on the resources of the national library.

Although a number of government-supported science establishments – various geological surveys, for example – already existed in the nineteenth century,

their number has grown considerably during the twentieth century. Their collections of literature are often important for research both by members of the establishment and by others in the same subject area. In addition, the establishments are often significant producers of their own research publications. Many new types of establishment appeared after the Second World War – for example, those dealing with atomic energy or space research – but financial stringency in the latter part of the century have, in a number of cases, led to reductions in their functions, amalgamation, or even closure.

The expansion in the number of research-oriented libraries, and in the size of their collections, has been paralleled by an increasing need for bibliographical control to aid the acquisition and retrieval of all this material. One result has been that the twentieth century has seen the appearance of detailed classification schemes that can be used as an aid to cataloguing and storing collections. Much of this development is due to the librarians, but others have contributed. For example, publishers have introduced ISBNs (International Standard Book Numbers) and ISSNs (International Standard Serials Numbers) to help identify their products. By far the most important innovation, however, has been the application of computers to the identification and retrieval of material. As with networking, much of the early work on this was concentrated on science, technology and medicine. The atomic energy and space programmes, both provided an important stimulus to progress. The overall result is that, despite the vast growth in publications, searching the literature can probably be done more comprehensively at the end of the century than it could at the beginning.

Collecting science publications

Despite the proliferation of science publishing, twentieth-century publications have some drawbacks from the point of view of the collector. This is not simply because they are more recent and more readily available. The growth of specialization and professionalization in science means that many of them are of little interest beyond a small group of specialists. Nevertheless, books by really outstanding scientists still attract attention. In the physical sciences, these are typically discussions of research that has already, at least in part, appeared in journals. Examples of this type are the various books written on radioactivity and nuclear physics by Marie Curie, Rutherford and their contemporaries, or Einstein writing on relativity. Away from the experimental sciences, books could still provide access to influential new thinking. Examples range from Wegener on continental drift to Freud on psychotherapy. Even here, examples are rarer in the second half of the century, but Wilson on sociobiology and Tinbergen or Lack on animal behaviour can be cited. In a similar way, technology books from earlier in the century tend to be more collectable. Specialist texts on early manned flight, or the railways during the steam era, for example, can be collectors' items. Some official reports – for

example, those reporting research developments during the Second World War – hold a similar interest.

The growing emphasis on journal papers has naturally turned collectors' attention to these. Thus, Einstein's papers published during 1905 – his *annus mirabilis* – are certainly desirable items. The increasing stress on journal publishing in the biological sciences has led to important developments appearing in these. The obvious example of a collectable item is the Crick and Watson note on DNA, published in *Nature* in 1953. In this case, the journal is well known, but some papers can be collectable because they appear in little-known sources. An example is the work for which Alfvèn ultimately received a Nobel Prize in physics: it appeared in a minor Swedish publication during the Second World War.

Historic papers exist today either as part of the journals in which they appeared, or as reprints/offprints. In the former case, there is the problem that individual issues of journals rarely come on the market. They are usually one of a set of issues that are being offered together. Indeed, most sets are likely to have been bound together in volume sequence. Back-runs of major journals are collectable items in their own right, so it rarely makes sense to break up a sequence for the sake of a single paper. Besides avoiding this problem, reprints/offprints are also more likely to provide association copies – more especially, they may be signed by the author(s). Published collections of papers by major twentieth-century scientists also exist, though they tend mainly to be bought by institutional purchasers.

Popular books by eminent scientists are more interesting items to collect in terms of readability. However, since they were usually produced in quantity, they are often quite readily available on the second-hand market, which tends to keep the prices down. Still, an association copy of a book such as Rachel Carson's *Silent Spring*, which had a continuing impact, would be well worth acquiring. Popular or semi-popular books on technology are often in greater demand, as are magazines dealing with technology. For example, some of the early discussions of spaceflight in both books and magazines are difficult to acquire (the same can be said of early science fiction).

The real question mark for collectors hangs over the future. If science publishing moves increasingly to an electronic base, how is material to be collected? Information that is available online is like books in print: it is continually accessible to anyone willing to pay the money. If it is not available online, the cost and effort of acquiring and storing the information soon exceeds the capabilities of an individual. Information on CD-ROM is an exception to this rule, for CD-ROMs can be purchased and exchanged in much the same way as books and journals. The main problem is that CD-ROMs are likely to be a transitional method of storing digital information, meaning that they might not be employed in this way for more than a few years. Besides limiting the amount of material available for collection, this implies that collectors will also need to collect and maintain all the associated hardware and software in order to access the information. Whatever the route that developments take, collection of scien-

tific material in digital form may not be an easy option for collectors in the immediate future.

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Chapter Nine

Scientific Bibliographies and Bibliographers, and the History of the History of Science

W.H. Brock

> Every investigation must begin with a bibliography, and end with a better bibliography.
>
> *George Sarton*

Bibliographies are keys to the vast accumulations of literature that are constantly growing, and can be compared with compasses guiding the traveller through unexplored regions. The objective may be clear, but the path tortuous, and much valuable material can be gleaned on the journey. Bibliographies devoted to scientific subjects are numerous but commonly embrace only history of science articles and monographs if they are written by historians rather than scientists. Although by no means the first historian of science, George Sarton (1884–1956), was the first to institutionalize and expand the subject academically.[1] He was a humanist and positivist for whom science and technology were the engines of human progress. His approach to the subject was unmitigatingly bibliographical, as exemplified by his encyclopaedic *Introduction to the History of Science* (3 vols in 5, Baltimore, 1927–48, reprinted Melbourne, Florida, 1975), which surveys the period from Homer down to 1400 and covers the Middle Ages, both East and West, in considerable detail. The importance of bibliography to the historian was underlined by Sarton in *Horus. A Guide to the History of Science* (Waltham, MA, 1952) which remains an interesting and attractive portrait of the field as it existed in the early 1950s before the subject

was revolutionized by social historians. Since the 1970s a starting point for any research involving key figures in history of science has been the *Dictionary of Scientific Biography* (*DSB*) edited by Charles C. Gillispie, 16 volumes (including one index volume) (New York, 1980), with two further volumes on twentieth-century scientists edited by Frederic L. Holmes (New York, 1981). All contributors were asked to cite existing bibliographies of scientists, or to provide guides where they did not exist. Although the results vary in quality, some (such as those for Euclid, Kepler and Pasteur) are first-class. In what follows only the most important single-author bibliographies will be mentioned. Historians of science themselves are the subject of a useful bibliography by S. A. Jaywardene and J. Lawes (1979), 'Biographical notices of historians of science: a checklist', *Annals of Science*, 36, 315–94.

Helpful essays on the history and development of the discipline of history of science are to be found in I. Spiegel-Rösing and D. J. de Solla Price (eds), *Science, Technology and Society. A cross-disciplinary perspective* (London, 1977); and P. Corsi and P. Weindling, (eds), *Information Sources in the History of Science and Medicine* (London, 1983). Also useful is M. Shortland and A. Warwick (eds), *Teaching the History of Science* (Oxford, 1989), which contains a certain amount of bibliographic information. Historical issues pertaining to the many different methods and approaches that are now taken in the study of the history of science are examined critically in Helge Kragh, *An Introduction to the Historiography of Science* (Cambridge, 1986). Also of continuing value is W. F. Bynum, E. J. Browne and Roy Porter (eds), *Dictionary of the History of Science* (London and Princeton, 1981). This is, in effect, a miniature encyclopaedia of the history of science comprising articles on general and specific topics of between 50 and 2000 words; longer essays carry bibliographical information.

Although not strictly bibliographies, it is probably worth drawing attention at this point to the many biographical dictionaries of value. They include Allen G. Debus, *World Who's Who in Science from Antiquity to the Present*, Marquis-Who's Who Library (Chicago, 1968), which is very comprehensive; David Millar et al., *Chambers Concise Dictionary of Scientists* (Cambridge and New York, 1959), which has a thousand short entries; John Daintith et al., *Biographical Encyclopaedia of Scientists* (2 vols, Institute of Physics, Bristol and Philadelphia, 1981; 2nd edn, 1983 and 1984), which seems to be identical to John Daintith et al., *Chambers Biographical Encyclopaedia of Scientists* (Edinburgh, 1983). All of these give basic information, but lack indications for further reading. Trevor Williams, *Collins Biographical Dictionary of Scientists* (4th edition, London, 1994) which contains about 1300 figures, includes some living scientists and in most cases useful suggestions for further reading are given; Roy Porter, *The Hutchinson Dictionary of Scientific Biography* (Oxford, 1994) is a largely unaltered reprint in amalgamated format of the six-volume series, *The Biographical Dictionary of Scientists: Biologists* (1983), *Chemists* (1983), *Astronomers* (1984), *Physicists* (1984), *Engineers and Inventors* (1985), and *Mathematicians* (1985). No bibliographical information is given. A very helpful

list is E. Scott Barr, *An Index to Biographical Fragments in Unspecialized Journals* (University of Alabama, 1973), which indexes memoirs ands obituaries from seven journals, including *American Journal of Science, Nature, Proceedings of the Royal Society*, and *Science*. The cut-off date is 1920 in all cases. Finally, almost on the scale of the *DSB* and making up in superb illustrative material what it lacks by way of detailed bibliographies is Edgardo Macorini (ed.), *Scienzati e tecnologi delle origini al 1875* (3 vols, Milano, 1975). Half of the third volume is given over to elaborate chronologies of scientific development up to 1900. Three further volumes with the same title deal with twentieth-century scientists and were published at Milano, 1974. Most of the entries in the latter are elaborated translations from McGraw-Hill's standard *Modern Men of Science* (2 vols, New York, 1966–68), which has been updated as McGraw-Hill, *Modern Scientists and Engineers* (3 vols, New York, 1980). The Italian version is sumptiously illustrated and, unlike its American counterpart, contains a limited amount of bibliographical information.

General Bibliographies

A monumental attempt at a complete list of published bibliographies was made by Theodore Besterman (1904–76) in his *A World Bibliography of Bibliographies, and of bibliographical catalogues, calendars, abstracts, digests, indexes, and the like*. The fourth edition in five volumes was published at Lausanne in 1965–66 and consists of an alphabetical dictionary arrangement of subjects down to 1963 inclusive, and covers 117,187 bibliographies arranged under 15,829 headings. History of science is to be found under individual sciences. An update of literature published between 1964 and 1974 was compiled by Alice F. Toomey under the same title in two volumes, Totowa, NJ, 1977. Rather less daunting than Besterman, and easier to use, is R. L. Collison, *Bibliographies. Subject and National. A guide to their contents, arrangements and use* (London, 1968), which includes two sections on science, and technology and industry.

A subject index of current bibliographies, both separately published and in periodicals, is issued three times a year, the December issue being a cumulative volume. *Bibliographic Index. A cumulative bibliography of bibliographies* (New York) has been published since 1937, and contains a high percentage of scientific material.

An early subject index to articles appearing in the publications of scientific societies during the eighteenth century was compiled by Jeremias David Reuss as *Repertorium Commentationum a Societatibus Litterariis Editorum* (Göttingen, 1801–21). This was published in 16 volumes: volume 1 covers natural history; volume 2 deals with botany and mineralogy; volume 3 is devoted to chemistry; volume 4 covers natural philosophy; and volumes 10 to 16 deal with science and medicine. A reprint was issued in 1961.

With the increasing sophistication of computer-based information services, historians of science now face the probability that bibliographic services will become more and more widely available in electronic forms. Some important existing bibliographies are already available on-line, such as the History of Science and Technology (HST) file produced by the research Libraries Group in the USA and issued by the Research Libraries Information Network (RLIN) subscription service; and the on-line version of the Italian bibliography of history of science, *Bibliografia Italiana di Storia della Scienza*. The former service already incorporates the *Isis* and *Technology and Culture* bibliographies mentioned below. These are carried back to 1976 and 1987 respectively. These electronic versions, unlike their paper counterparts, enable sophisticated researches to be made using index words. Other electronic forms of otherwise conventionally-printed bibliographic databases will be noted below.

The heading 'bibliography' often includes various types of compilation which, strictly speaking, are not entitled to that honour. The *Bibliothecae*, for example, are seldom true bibliographies, but are either collections of writings or catalogues of collections. Nevertheless, while these, as well as catalogues of libraries and personal collections, are rarely exhaustive, they can be of assistance in research. An example of early *Bibliothecae* is E.A. Zuckold's *Bibliotheca Historico-Naturalis, Physico-Chemica et Mathematica*, published at Göttingen in 1852. Many later examples will be cited below at relevant points. Another vital source of bibliographical information is Johann Christian Poggendorff's *Biographisch-literarisches Handwörterbuch zur Geschichte der exacten Wissenschaften*. Currently in its eighth series, it has been appearing in parts (Berlin, 1858 onwards). Reprints of many volumes have been published in Leipzig and Amsterdam. Volumes 1 and 2 cover the period up to 1858; volume 3, 1858–83; volume 4, 1883–1904; volume 5, 1904–22; volume 6, 1923–31; and volume 7a, 1923–53, which was published as four volumes (in five), 1956–62. Volume 7b in 9 volumes appeared *seriatum* between 1967 and 1992. Many of the entries in the first three volumes were based on personal information given to Poggendorff by contemporary scientists and not otherwise available. Poggendorff only covers the physical sciences, and is arranged alphabetically by scientists, providing abbreviated biographies, with lists of publications, including both books and articles in periodicals. Hans Salié[2] has provided a brief biography of Johann Christian Poggendorff (1796–1877), who was born in Hamburg and trained as a pharmacist. He became editor of *Annalen der Physik und Chemie* in 1824, and held the post for 52 years. He lectured on the history of physics at Berlin University, and was the author of *Geschichte der Physik* (Leipzig, 1879) which was reprinted in 1964. Salié gives an historical description of Poggendorff's *Handwörterbuch* and its continuation under various compilers, including the proposals that have secured its continuing appearance.

The Royal Society of London was responsible for the compilation and publication of the *Catalogue of Scientific Papers* which was published in four series in 19 volumes at London (4th series, Cambridge) from 1866 to 1925. This

consists of an author index of articles in over 1500 scientific periodicals published between 1800 and 1900. A subject index (three volumes in four) also appeared between 1908 and 1914, but this will be found of little value by historians of science. The first series (volumes 1 to 6) covers the years 1800 to 1863; the second series (volumes 7 and 8) covers 1864 to 1873; series three (volumes 9 to 11) covers 1874 to 1883; volume 12 is a supplementary volume devoted to 1800 to 1883; and the fourth series (volumes 13 to 19) is devoted to the years 1884 to 1900. The volumes have been reprinted. Historians interested in twentieth-century science will also find a use for the continuation of the Royal Society's *Catalogue* in the *International Catalogue of Scientific Literature*, issued by the Royal Society for the International Council of Scientific Workers. This was published in 14 annual issues, each consisting of 17 sections devoted to branches of science, covering the years 1901 to 1914. The volumes are arranged alphabetically by authors, with classified subject indexes. This, too, has been reprinted. Literature searches for scientific papers published after 1914 can be achieved through the abstracting journals familiar in all science departmental libraries, such as *Chemical Abstracts* (founded 1907), *Zoological Record* (founded 1864), etc.

The library of Sir William Osler (1849–1919) is chiefly of medical significance, but the catalogue of the collection, published as *Bibliotheca Osleriana: a catalogue of books illustrating the history of medicine and science, collected, arranged and annotated by Sir William Osler, and bequeathed to McGill University* (Oxford, 1929) contains many items of purely scientific interest. About 7600 bound volumes are listed therein, and the annotations render the catalogue eminently readable and of increased historical importance. Lloyd G. Stevenson contributed an introduction to the reprint of the *Bibliotheca Osleriana* published by McGill University, Montreal, 1969. In the same category can be mentioned a bibliography by Fielding H. Garrison (1879–1935), which was revised by Leslie T. Morton and published as *A Medical Bibliography (Garrison and Morton): an annotated check-list of texts illustrating the history of medicine* (5th edn, London: Scolar Press, 1991). This contains 6809 entries classified and annotated, with reasonably adequate author and subject indexes. Biology, anthropology, microscopy, zoology and comparative anatomy, anatomy and physiology are among the subjects included that are of particular interest to historians of science. *The Bibliotheca Walleriana. The books illustrating the history of medicine and science collected by Dr. Erik Waller and bequeathed to the Royal University of Uppsala. A catalogue compiled by Hans Sallander* (two vols, Stockholm, 1955), contains sections devoted to natural sciences, alchemy and chemistry, physics, botany, zoology, etc., and lists over 150 incunabula. These were collected by Erik Waller (1875–1955), a native of Sweden.[3] In the same genre is Jean S. Gottlieb, *A Checklist of the Newberry Library's Printed Books on Science, Medicine, Technology and the Pseudosciences, ca. 1460–1750* (New York, 1992).

Harrison D. Horblit's *One Hundred Books Famous in Science* (New York, 1965) was published by the Grolier Club, and contains entries ranging from

Pliny's *Historia Naturalis* (1469) to Einstein's *General Theory of Relativity* (1916). Arranged alphabetically by authors, with a chronological index, entries have brief annotations, with generally accurate collations and useful illustrations. A similar work containing 424 numbered entries was edited by John Carter and Percy H. Muir as *Printing and the Mind of Man. A descriptive catalogue illustrating the impact of print on the evolution of western civilization during five centuries* (London, 1967). This contains extensive, scholarly annotations to each item, with useful biographical and bibliographical information, and many of the entries are of scientific interest.

A bibliography for early material is published as *L'Année philologique; bibliographie critique et analytique de l'antiquité gréco-latine. Première année 1927 ... Bibliographie des années 1924–26* (Paris, 1928 onwards). This includes a section 'Sciences et métiers' in each annual volume, forming a useful bibliography of books and articles in periodicals on ancient science. Entries are classified as generalia (including general histories of science); astronomie; mathématiques; chimie et physique; sciences naturelle, etc. Early printed books are also well represented in Diana H. Hook and Jeremy M. Norman, *The Haskell F. Norman Library of Science and Medicine* (2 vols, San Francisco, 1991).

François Russo compiled a selective bibliography of particular value to historians of science. Entitled *Elements de Bibliographie de l'Histoire des Sciences et des Techniques* (2nd edn, Paris, 1969), this contains a division devoted to the bibliography of the study of history of science, including sections on methods; biographies of historians of science; societies and institutions arranged alphabetically by country; congresses, libraries and museums. The second part is concerned with printed sources, encyclopaedias, dictionaries, biographical dictionaries, bibliographies, catalogues of manuscripts, lists of scientific periodicals, followed by the actual titles and bibliographical details of periodicals on the history of science, and collective biographies. The various historical periods are then covered from antiquity, the Middle Ages, and the sixteenth to the twentieth centuries. The same author's *Libres Propos sur l'Histoire des Sciences* (Paris, 1995), is aimed solely at French students beginning to study the subject. A shorter and even better German equivalent of Russo's *Elements* is Burghard Weiss, *Wie finde ich Literatur zur Geschichte der Naturwissenschaften und Technik* (Berlin, 1985; 2nd enlarged edn, 1970). Besides being an excellent guide to the literature of the history of science and technology, including bibliographies, Weiss provides useful information on the world's libraries and archives. Russo and Weiss's English-language equivalent is Gordon L. Miller, *The History of Science. An annotated bibliography* (Pasadena, CA, 1992).

Pietro Corsi and Paul Weindling have edited a helpful volume of *Information Sources in the History of Science and Medicine* (London, 1983) that has already been mentioned in connection with the study of the history of science. This volume is divided into four sections, each containing bibliographical and historical information. The first, general part, considers the main features of the history of science and medicine in their relationships with anthropology, philosophy,

religion and the social sciences. A second section deals with general literature, major institutions and research methods. The third section consists of bibliographical review essays on the physical sciences, mathematics, chemistry and the life sciences, as well as scientific instruments and medicine since 1500. The final section reviews the literature on non-European science, including the Americas.

A group of historians of science at the University of Leeds, R.C. Olby, G.N. Cantor, J.R.R. Christie and M.J.S. Hodge, have collectively edited the very useful *Companion to the History of Science* (London, 1990; paperback 1996). While not strictly a bibliography, its 67 sections nevertheless offer a ready entry into both the historiography of history of science and a wide range of topics, interpretations and perennial themes within the discipline. A similar format, albeit on an even larger scale, is employed in W.F. Bynum and Roy Porter, (eds), *Companion Encyclopaedia of the History of Medicine* (2 vols, London and New York, 1993). Many of its 72 chapters, each of which incorporates a bibliography, contain material that bears upon the history of science and technology as much as medicine. Other *Companions* in the history of mathematics and technology are mentioned below.

S.A. Jayawardene has compiled *Reference Books for the History of Science: a handlist* (London, 1982), which lists 1034 items arranged into 44 sections and divided into three parts covering the history of science and its sources, history and related subjects, and general reference sources. Most of the works listed are to be found on the shelves of the Science Museum Library at South Kensington, probably the richest library in Great Britain for secondary material on the history of science.

In addition to the *DSB*, an invaluable guide to current literature is provided by the 'Critical bibliography of the history of science and its cultural influences', published in *Isis* since 1913 and as an annual supplement since 1954. Cumulative editions of these bibliographies were assembled by Magda Whitrow and published as *A Bibliography of the History of Science formed from the ISIS Critical Bibliographies 1–90, 1913–65* (6 vols, London, 1971–84). Volumes 1 and 2 deal with personalities and institutions; volume 3, subjects, volumes 4 and 5, periods and civilizations, and volume 6 is an author index. The project was continued by John Neu in his *Isis Cumulative Bibliography, 1966–1975*, which appeared in two volumes, London, 1980 and 1984, the first covering personalities and institutions, the second, subjects, periods and civilizations. Two further similarly arranged volumes covering 1976–85 appeared in 1990. Another four volumes appeared in 1997, namely John Neu, ed., *Isis Cumulative Bibliography, 1986–95*, Science History Publications for the History of Science Society: Canton, MA. An annual bibliography of the history of technology is also published by *Technology and Culture* and will be mentioned in the final section below. As noted above, both *Isis* and *Technology and Culture* now have their annual bibliographies available electronically.

The Australian librarian and historian of science, Robert Mortimer Gascoigne, has compiled two extremely useful complementary catalogues: *A Historical*

Catalogue of Scientists and Scientific Books from the Earliest Times to the Close of the Nineteenth Century (New York, 1984); and *A Historical Catalogue of Scientific Periodicals, 1665–1900, with a survey of their development* (New York, 1985). Publications concerning Victorian scientific periodicals are also critically surveyed in a bibliographical essay by W.H. Brock in J. Donn Vann and Rosemary T. VanArsdel (eds), *Victorian Periodicals and Victorian Society* (Toronto, 1994).

A specialist bibliography on what has been called 'the science of science' or scientometrics, is Roger Hahn, *A Bibliography of Quantitative Studies on Science and its History* (Berkeley, 1980). There are a few notable national bibliographies such as Margaret W. Batschelet, *Early American Books, Pamphlets and Broadsides* (Metsuchen, NJ, 1990); Marc Rothenberg, *The History of Science and Technology in the United States: A critical and selective bibliography* (New York, 1982), whose 832 entries concentrate on literature published since 1940; a sequel to Rothenberg's bibliography covering the secondary literature between 1980 and 1987, was issued under the same title in 1993 and contains another 653 entries. For Canada, R. Alan Richardson and Bertrum H. Macdonald have compiled *Science and Technology in Canadian History. A bibliography of primary sources to 1914* (105 microfiches, Thornhill, Ontario, 1987). For Spain there is José M. Lopez Pinero, M.P. Reig and L. G. Ballester (eds), *Bibliografia historica sobre la ciencia y la téchnica en Espana* (Valencia, 1973) which covers the period from the eighteenth century to the present. For China there is Genevieve C. Dean, *Science and Technology in the Development of Modern China. An annotated bibliography* (London, 1974); while S. Nakayama and N. Sivin have published a comprehensive guide to Western-language literature on Chinese science in their monograph *Chinese Science: Explorations of an Ancient Tradition* (Cambridge, Mass., 1973), pp. 279–314. Another *Annotated Bibliography on Science and Technology in China* (Washington, DC, 1976), places emphasis on modern China, but like Dean's work, it offers some coverage of literature on Chinese traditional science. Similar bibliographic essay-guides to Islamic, Indian and Chinese science and medicine, by Emilie Savage-Smith, T.J.S. Patterson and Christopher Cullen respectively are included in the previously mentioned *Information Sources* edited by Corsi and Weindling. A bibliography of Russian work on the history of science, *Istorija estestvoznanija,* has been published in several volumes from Moscow since 1949. Information on English- and Japanese-language material on Japanese science is best gleaned from Shugeru Nakayama's essay, 'Japanese scientific thought', in *DSB*, vol. 15, pp. 728–58; and from James R. Bartholomew, *The Formation of Science in Japan. Building a Research Tradition* (New Haven and London, 1989). There exists no general survey of the literature of Scandinavian science, though helpful hints can be gleaned from the *Uppsala Newsletter. History of Science* issued biannually by the Office for History of Science at Uppsala University. This has been published since 1984 'as an attempt to give surveys and information about [the field] in Scandinavia'. Other national bibli-

ographies, where they exist, are best traced through the *ISIS Critical Bibliographies* mentioned above. In addition, many national journals publish regular bibliographies of books and articles concerning the development of science, medicine and technology within their national frontiers (e.g. *Historical Records Australian Science, Kwartalnik Historii Nauki I Techniki*, published by the Polish Academy of Sciences).

Historians whose interests are primarily focused on non-western science should consult the *ISIS Critical Bibliography*, as well as Helaine Selin, *Science Across Cultures: an annotated bibliography of books on non-western science, technology and medicine* (New York, 1992). A specialist bibliography dealing with the medieval period is Claudia Kren, *Medieval Science and Technology. A selected annotated bibliography* (New York, 1985). Its 1470 items include sections on education and philosophy, as well as the science and technology of the title.

The annual *Isis* bibliography is complemented by two other regular publications. The first is the quarterly *Bulletin Signalétique*, No. 522, of the Centre National de la Recherche Scientifique (CNRS), section 522 being subtitled *Histoire des sciences et des techniques*. Unlike the *Isis* bibliography, which merely lists book reviews, this offers abstracts of reviews. The French database, FRANCIS, now incorporates the *Bulletin*, which no longer appears in printed format. Despite being primarily devoted to the history of medicine, the *Bibliography of the History of Medicine*, published by the Institutes of Health, Bethesda, MA, and the Wellcome Institute for the History of Medicine's *Current Work in the History of Medicine*, are in practice very eclectic, usually offering useful references to books and articles on the chemical and biological sciences. The former is available electronically on HISTLINE® which can be accessed from any computer terminal that is linked with the National Library of Medicine's MEDLARS® (Medical Literature Analysis and Retrieval System). Following the publication of volume 28, which surveyed the years 1990–93, the *Bibliography of the History of Medicine* has been available only in this electronic medium. *Current Work in the History of Medicine*, as well as the other vast resources of the Wellcome Institute Library, whose printed books, serials and iconographic materials go way beyond the history of medicine, can now be consulted through the Wellcome Institute Library Database and Catalogue (WILDCAT) either through the Joint Academic Network (JANET) or through JANET on the Internet.[4]

A helpful way of tracing theses by history of science discipline is found in Roger R. Bilboul's *Retrospective Index to Theses of Great Britain and Ireland 1716–1950* in seven volumes (Oxford and Santa Barbara, CA, 1976–77). The third, fourth and fifth volumes list theses in the life sciences, physical sciences and chemical sciences respectively.

Compiled at the request of the Deutsche Gesellschaft für Geschichte der Medizin, Naturwissenschaft und Technik, volume 1 of *Index zur Geschichte der Medizin und Biologie* was edited by Walter Artelt, and covers 1945–48, having

been published in 1953. Volume II, edited by Johannes Steudel, Wilfried Ricker and Claus Nissen, covers 1949–51/52, and was published in Munich, 1966. Although devoted primarily to medical history, the history of biology is adequately represented.

The roles of women in and outwith science have attracted a growing amount of attention. A small-scale guide to this literature is provided by Audrey B. Davis in *Bibliography on Women: with special emphasis on their roles in science and society* (New York, 1974). Another useful starting point is Susan E. Searing (ed.), *The History of Women and Science, Health and Technology. A bibliographic guide to the professions and the disciplines* (Madison, 1988). Finally two serendipitous sources for historians of science: Dena Attar, *A Bibliography of Household Books published in Britain 1800–1914* (London, 1987), which contains surprises insofar as many scientists wrote popular books in this area (for example the chemist, Sir William Jackson Pope); and Elizabeth Driver, *A Bibliography of Cookery Books published in Britain 1875–1914* (London and New York, 1989), where the same phenomenon will be found.

Mathematics

The bibliography of mathematics is abundant, and includes some very interesting examples of the art. G.A. Miller's *Historical Introduction to Mathematical Literature* (New York, 1921) was first published in 1916, the author being professor of mathematics at the University of Illinois. The work is actually a general history of mathematics, but contains much biographical and bibliographical information. Kenneth O. May, *Bibliography and Research Manual of the History of Mathematics* (Toronto, 1973), concentrates on the secondary literature published since 1968 and is a *tour de force* of information. It is usefully complemented by Joseph W. Dauben (ed.), *The History of Mathematics from Antiquity to the Present* (New York, 1982); and by I. Grattan-Guinness (ed.), *Companion Encyclopaedia of the History and Philosophy of the Mathematical Sciences* (2 vols, London and New York, 1994). The latter's 13 comprehensive sections review the literature of ancient and non-Western mathematics; Western Middle Ages and Renaissance; calculus and analysis; functions and series; logics, set theories and the foundations of mathematics; algebras and number theory; geometries and topology; mechanics and mechanical engineering; physics, mathematical physics and electrical engineering; probability and statistics; education and institutions of mathematics; mathematics and culture; and a final section of references and sources of information. In itself, it forms a splendid complement to the Leeds historians' *Companion* in the same series.

The earliest bibliography of mathematics was that by Cornelius à Beughem, a magistrate and librarian at Emmerich, who compiled several other bibliographies. His *Bibliographia mathematica et artificiosa novissima perpetuo contuanda, seu conspectus primus catalogi liborum mathematicorum ... quotquot currente*

hoc semiseculo ... in quavis lingua ... typis prodierunt (Amsterdam, 1685 and 1688) lists 3000 entries. In the next century appeared Johann Ephraim Scheibel's *Einleitung zur mathematischen Bücherkenntniss,* published in 18 parts at Breslau between 1769 and 1778, and containing 10,000 items. A four-volume work by Abraham Gotthelf Kästner, entitled *Geschichte der Mathematik. Geschichte der Künste und Wissenschaften* (Göttingen, 1796–1800), lists 5000 mathematical works. Almost simultaneously appeared Friedrich Wilhelm August Murhard's *Literatur der mathematischen Wissenschaften* (5 vols, Leipzig, 1797–1805), containing 10,000 entries. Several other mathematical works of bibliographical interest were published in the nineteenth century, the first two, by Johann Wolfgang Müller, being entitled *Auserlesene mathematische Bibliothek* (Nuremberg, 1820) and *Repertorium der mathematische Bibliothek* (2 vs, Augsburg, 1822–25). Only the first part of J. Rogg's *Handbuch der mathematischen Literatur vom Anfange der Buchdruckerkunst ... Erste Abheilung, welche die arithmetischen und geometrischen Wissenschaften enhält,* appeared at Tübingen, 1830, but it was continued by Ludwig Adolph Sohncke in his *Bibliotheca mathematica. Verzeichniss der Bücher über die gesammten Zweige der Mathematik ... welche in Deutschland und dem Auslande von Jahre 1830 bis Mitte des Jahres 1854 erschienen sind* (Leipzig, 1854). Interestingly, this was also issued with a title-page in English.

James Orchard Halliwell (afterwards Halliwell-Phillipps) (1820–89) was a literary figure keenly interested in Shakespeareana and in mathematics. He made several important collections of books and pamphlets, which he sold at intervals, and his library of early mathematical and astronomical manuscripts was disposed of in 1840. Halliwell had previously published a catalogue of these in 1839, and he then appears to have concerned himself with literary work and controversy. He published *Rara mathematica* in 1839 (reprinted New York, 1970), and edited for the Historical Society of Science, which he founded in 1841, *A Collection of Letters Illustrative of the Progress of Science in England from the Reign of Queen Elizabeth to that of Charles the Second* (London, 1841). This was reprinted in 1965, together in one volume with *Popular Treatises on Science Written During the Middle Ages in Anglo-Saxon, Anglo-Norman and English. Edited from the original manuscripts by Thomas Wright.* Halliwell was a precocious, rather notorious figure, and further information on his career is provided by A.N.L. Munby.[5]

A fascinating work, limited in usefulness by its small size, was compiled by the professor of mathematics at University College, London, Augustus De Morgan (1806–71), who also wrote several mathematical works of significance. His bibliographical venture was published as *Arithmetical Books from the Invention of Printing to the Present Time: being brief notices of a large number of works drawn from actual inspection* (London, 1847), and lists 500 entries. No entry was taken from a catalogue, but every book was handled by the author, who contributed a lengthy introduction. Entries are in chronological order, and arranged by place and date of publication, author, title and size being indicated.

Full annotations, the best feature of the work, are included, as is also an author index. This book was reprinted in 1966 with an introduction by A.R. Hall which characterizes De Morgan as a keen collector books and a pioneer bibliographer.[6] A fairly complete list of De Morgan's writings is to be found in G.C. Smith, *The Boole-De Morgan Correspondence, 1842–1864* (Oxford, 1982); and Adrian Rice's useful article, 'Augustus De Morgan: historian of science', *History of Science*, 34 (1996), 201–40, provides a bibliography of his many historical works.

Two valuable biobibliographies of mathematicians and instrument makers were prepared by the late E.G.R. Taylor, *The Mathematical Practitioners of Tudor and Stuart* (Cambridge, UK, 1970); and *The Mathematical Practitioners of Hannoverian England 1714–1840* (Cambridge, 1966), the latter listing over 2000 surveyors and instrument makers. Taylor's work was continued on an even larger scale by the late Peter Wallis who began work on 'A biobibliography of British mathematics and its applications' in 1967. Part II, covering the period 1701–60, was edited by R.V. and P.J. Wallis at Newcastle in 1986, and included nearly 1100 authors and 8000 editions. Part I, covering the seventeenth century, is still in preparation; and Part III, an *Index of British Mathematicians, 1701–1800* (Newcastle, 1993), records 20,000 names alphabetically, citing their names, addresses and the titles of any books they subscribed to, and the source of information or further reference. Mathematics is here treated broadly to include teachers and practitioners of astronomy, navigation, surveying and architecture, as well as of pure mathematics. While the computer-generated format of this *Index* may appear daunting and not exactly user-friendly, a wealth of information here awaits further exploitation.

Although limited in scope, being confined to Germany and Italy respectively, the following two works are worthy of note. A. Erlecke's *Bibliotheca Mathematica. Systemat. Verzeichniss d.b. 1870 in Deutschland auf d. Gebieten der Arithmetik, Algebra, Analysis, Geometrie ... Astronomie* (Halle, 1873); and Pietro Riccardi's *Bibliotheca matematica italiana dalla origine della stampa ai primi anni del secolo XIX* (Modena, 1893; reprinted Milano, 1952). The latter, a monumental work, is arranged alphabetically, with annotations, an appendix and chronological tables. Another Italian bibliography, *Bibliografia sui fondamenti della geometria*, by R. Bonola, was published in 1899.

Originally published as series of articles,[7] D. Bierens de Haan's *Bibliographie néerlandaises historique-scientifique des ouvrages importants dont les auteurs sont nés aux 16e, 17e et 18e siècles sur les sciences mathématiques et physiques, avec leur applications* was published in Rome in 1883, and an unchanged reprint was published in Nieuwkoop in 1960. This contains 5651 entries, with useful bibliographical descriptions of every work of importance.

The first important mathematical bibliography to appear in the twentieth century was E. Wölffing's *Mathematischer Bücherschatz* (Leipzig, 1903). This is a classified bibliography of the most important literature on pure mathematics published during the nineteenth century, but excludes periodical literature. In

1908 appeared David Eugene Smith's *Rara Arithmetica. A catalogue of the arithmetics written before the year MDCI, with a description of those in the library of George Arthur Plimpton of New York* (Boston and London), listing nearly 1200 items. Full descriptions, with useful annotations and numerous facsimiles, are included, and Part 2 is devoted to manuscripts, indexes of dates, names, places and subjects. G.A. Plimpton died in 1936 and his collection is now in the Low Memorial Library at Colombia University. An addenda to the catalogue was published by Smith as *Addenda to Rara Arithmetica* ... (Boston and London, 1939). Smith's *Rara Arithmetica* was reprinted with De Morgan's above-mentioned *Arithmetical Books* at New York in 1970.

A chronological catalogue with extensive author and subject indexes was published for the University of St Andrews, and was compiled by Duncan M.Y. Sommerville as *Bibliography on Non-Euclidean Geometry Including the Theory of Parallels, the Foundations of Geometry, and Space of n Dimensions* (London, 1911). This lists over 4000 publications, but the entries are very brief and without annotations.

Two works of particular American appeal complete our survey of mathematical bibliography. L.G. Simon's *Bibliography of Early American Textbooks on Algebra Published in the Colonies and the United States through 1850; together with a characterisation of the 1st edition of each work* (New York, 1936); and Louis C. Karpinski's *Bibliography of Mathematical Works Printed in America to 1850* (Ann Arbor and London, 1940). In the latter, most of the major items have reproductions of their title-pages in facsimile, and there is an historical introduction, commencing with the British background. The work lists 1092 titles printed in the America up to 1850, with a total of 2998 titles and subsequent editions, subsequent editions being listed with these. Locations of items are given, but full bibliographical descriptions are not provided. Indexes of authors, subjects, non-English and Canadian works, and of printers and publishers, complete this remarkable piece of bibliographical research.

Periodical bibliographies of mathematics include *Bulletin de Bibliographie, d'Histoire et de Biographie mathématiques* (8 vols, 1855–62); *Bullettino di Bibliografia e di storia delle scienze matematiche e fisiche*, founded and edited by Baldassare Boncompagni (1831–94) and published at Rome from 1868 to 1887, a reprint of which appeared in 1964; *Revue semestrielle des publications mathématiques* (Amsterdam and Leipzig, 1893–1934); *Jahrbuch über die Fortschritte der Mathematik*, issued from Berlin from 1868 to 1934; *Zentralblatt für Mathematik* (Berlin, 1931 to date); and *Mathematical Reviews*, published by the American Mathematical Society since 1940, an international organ of high repute, and a most significant reference tool for the subject.

Finally, attention must be drawn to Louise S. Grinstein and Paul J. Campbell (eds), *Women of Mathematics* (New York and London), a biobibliographic sourcebook covering some 50 women mathematicians from the eighteenth to the twentieth centuries.

Astronomy

F. Leigh Gardner's *Bibliotheca Astrologica. A Catalog of Astrological Publications of the 15th through to the 19th Centuries*, which was privately printed in 1911, was reprinted at Hollywood, California, in 1977. Marianne Winder[8] has published a bibliography of German astrological works printed between 1465 and 1600, providing locations of those housed in London libraries. This included writings in German, by German-speaking people, and translations of foreign works into German. The various editions of a work are arranged chronologically, and there are indexes of authors, printers and publishers.

Bibliographies of astronomy are not numerous, and the next item to be mentioned is very specialised, covering only publications printed in Germany up to 1630. This is Ernst Zinner's *Geschichte und Bibliographie der astronomischen Literatur in Deutschland zur Zeit der Renaissance* (Leipzig, 1941) which contains 5236 numbered entries. A similar bibliography listing 2000 works printed up to the year 1650 is entitled *Astronomische chronologische Bibliographie. Einleitung zur mathematischen Bücherkenntniss* (Breslau, 1784–98). Produced by Johann Ephraim Scheibel, this was also published under the title *Astronomische Bibliographie.* Johann Friedrich Weidler's *Bibliographia astronomica* was published at Wittenberg in 1755 and contains 1250 items. A French bibliography listing 5000 entries was compiled by Joseph Jérome Le Français de La Lande, and published at Paris in 1803 as *Bibliographie astronomique; avec l'histoire de l'astronomie depuis 1781 jusqu'à 1802.* This is arranged in chronological order. On a larger scale we have the work by Jean Charles Houzeau (1820–88) and Albert Lancaster (1849–1908), published at Brussels from 1882 to 1889 as *Bibliographie générale de l'astronomie, ou catalogue méthodique des ouvrages, des mémoires et des observations astronomiques publiés depuis l'origine de l'imprimerie jusqu'en 1880,* two volumes (in three). Volume 1, Part I, is dated 1887; Part 2 bears the date 1889; and volume 2 was published in 1882. Houzeau was director of the Observatory at Brussels, and his work is classified, with an author index. A list of periodicals is included, as is also a bibliography of astrology. In 1964 a new edition of this was published as two volumes in three, with important additional material by D.W. Dewhirst. An adequate index of authors, a new introduction, short biographies of Houzeau and Lancaster, and a rearrangement of the text now facilitates reference to this primary bibliographical source.

Houzeau is now usefully complemented by David De Vorkin, *The History of Modern Astronomy and Astrophysics. A selected annotated bibliography* (New York, 1982), which contains over 1400 entries. Although not yet complete, attention must also be drawn to Paul Luther, *Bibliography of Astronomers. Books and pamphlets in English by and about astronomers,* volume 1 (Bernardston, MA, 1989). Produced in a limited edition of only 500 copies, this first volume compiles information on 14 astronomers, including Airy and Lockyer. A meritorious and extremely useful feature is the inclusion of 'amateurs' and popularizers such as Richard A. Proctor.

Two exhibition catalogues of 1994 are also useful: *Sphaera Mundi. Astronomical Books 1478–1600*, is an illustrated catalogue of an exhibition celebrating the 50th anniversary of the Whipple Museum of the History of Science, Cambridge, arranged by Jim Bennett and Bertoloni Meli; another exhibition arranged by Angus Macdonald and Alison D. Morrison-Low at the National Museums of Scotland, Edinburgh, is entitled *A Heavenly Library. Treasures from the Royal Observatory's Crawford Collection,* it being the gift to the British government of James Ludovic Lindsay (1847–1913), the 26th Earl of Crawford. This superb collection, which includes Charles Babbage's library, was catalogued by Ralph Copeland in *A Catalogue of the Crawford Library of the Royal Observatory Edinburgh* (Edinburgh: HMSO 1890). This is worth consulting, among other purposes, for the history of comets.[9] The best-known of these, Halley's comet, is surveyed magnificently by Ruth S. Freitag in *Halley's Comet. A bibliography* (Washington, DC, 1984). This includes material on popular reactions to the comet's appearance. Two astronomical periodicals are also worthy of note from the bibliographical viewpoint. The first, *Jahrbuch der Astronomie und Geophysik*, was published at Leipzig in 23 volumes from 1890 to 1912, and the 24th and final volume was entitled *Klein's Jahrbuch der Astronomie*. The *Astronomischer Jahresbericht,* Berlin, has appeared since 1899.

Physics

Bibliographies of interest to the historian of physics are innumerable, but three modern ones will be found particularly helpful. They are R.W. Home (with the assistance of Mark J. Gittins), *The History of Classical Physics. A selected, annotated bibliography* (New York, 1984), which covers the period 1700–1900 with about 1200 entries; Stephen G. Brush and Lanfranco Belloni, *The History of Modern Physics. An international bibliography* (New York, 1983), which covers the subject since the advent of X-rays in 1895; and Stephen G. Brush and Helmut E. Landsberg, *The History of Geophysics and Meteorology. An annotated bibliography* (New York, 1985), which clearly is also of value to the historian of geology.

The most general older bibliographies of the subject include Gustav Theodor Fechner's *Repertorium der Experimentalphysik, enthaltend eine vollständige Zusammenstellung der neuern Fortschritte dieser Wissenschaft,* in three parts (Leipzig, 1832), listing 2500 items; Sir Francis Ronalds' *Catalogue of Books and Papers Relating to Electricity, Magnetism and the Electric Telegraph* (London, 1880); *A Bibliography of Electricity and Magnetism, 1860–1883, with Special Reference to Electro-technics* (London, 1884), by Gustav May, of which a German edition was published in Vienna in the same year. William D. Weaver (ed.), *Catalogue of the Wheeler Gift of Books, Pamphlets and Periodicals in the Library of the American Institute of Electrical Engineers* (2 vols, New York, 1909). This interesting library was originally created by the British electrical

engineer Josiah Latimer Clark (1822–98), but has been dispersed from the holdings of its initial purchasers. Most of the collection is now housed at the Linda Hall Library, Kansas City, Missouri, a library dedicated to science and technology holdings. Paul Fleury Mottelay's *Bibliographical History of Electricity and Magnetism, Chronologically Arranged. Researches into the domain of the early sciences, especially from the period of the revival of scholasticism, with biographical and other accounts of the most distinguished natural philosophers throughout the Middle Ages* (London, 1922), commences at 2637 BC (*sic*) and finishes with Michael Faraday, and is a chronological history, with annotations, numerous references, illustrations and a very full index. Another collection, rich in unusual Scandinavian and European material, is Stig Ekelöf (ed.), *Catalogue of Books and Papers Relating to the History of Electricity in the Library of the Institute for Theoretical Electricity, Chalmers University of Technology* (2 vols, Göteborg, 1964–66). The compiler's own library, the first volume deals with works published before 1820; the second from 1820 to the 1960s. Also interesting is Judith A. Overmier and J.E. Senior (eds), *Books and Manuscripts of the Bakken* (Metuchen, NJ, 1992), which catalogues the library of the unusual Museum of Electricity in Life at Minneapolis.

The major, general periodicals are *Physics Abstracts*, issued monthly by the Institution of Electrical Engineers as Section A of *Science Abstracts*, London, and published since 1898; *Die Fortschritte der Physik*, Brunswick, published between 1845 and 1918 and continued since 1920 in conjunction with *Bleiblätter zu den Annalen der Physik* (Leipzig, 1877–1919) as *Physikalische Berichte*; and since 1920 the Société Francaise de Physique has published *Le Journal de Physique et le Radium: Revue Bibliographiques*, which appears from Paris.

Reprints of outstanding papers in the history of physics have appeared in W.F. Magie's *A Source Book in Physics* (Cambridge, Mass., 1963), containing extracts covering 1600 to 1900, with biographical and explanatory notes; and *Classical Scientific Papers. Physics, Facsimile Reproductions of Famous Scientific Papers*, with an introduction by Stephen Wright (London, 1964); and E.A. Davis (ed.), *Science in the Making* which reproduces papers from the pages of *Philosophical Magazine* in four volumes. The first volume, covering the period 1798–1850, was published in 1995; two further volumes appeared in 1996 and 1998.

The principal founders of the Scientific Revolution, Copernicus, Galileo, Kepler and Newton, have attracted their own bibliographers. Henryk Baranowski's *Biografia kopernikowska 1509–1955* reached a second edition at Warsaw in 1973, and was complemented by an annotated critical bibliography covering the period 1939–58 by E. Rosen in his *Copernicus, Nicolaus; Rheticus, Georg. Three Copernican Treatises* (New York, 1959), pp. 201–69. Owen Gingerich's compilation of a census of ownership and use of extant copies of the first and second editions of Copernicus's *De Revolutionibus* is described in his 'Great Copernicus chase', *American Scholar*, 49 (1979), 81–88, but the final results have not yet been published.[10] For Galileo, see A. Carli and A. Favaro

(eds), *Bibliografia Galileiana, 1568–1895* (Rome, 1896); this was extended by Giuseppe Boffito in a *Primo Supplemento, 1896–1940* (Rome, 1943), which also indexed the Carli-Favaro bibliography; and by Elio Gentili in *Bibliografia Galileiana, fra i due centenari (1842–1964)* (Varese, 1966). Gentili's work was also complemented by E. McMullin's coverage of work on Galileo published between 1940 and 1964 in his *Galileo, Man of Science* (New York, 1967). The great German Kepler scholar, Max Caspar, published *Bibliographia Kepleriana. Eine Führer durch das Gedruckte Schriftum von Johannes Kepler* (2nd edn, Munich, 1968). Martha List has published a supplement to this in *Vistas in Astronomy*, 22 (1978), 1–18, but the compendious bibliography attached to O. Gingerich's Kepler entry in the *DSB* must also be consulted. Inevitably the work of Isaac Newton has attracted bibliographies of great importance. Peter and Ruth Wallis, *Newton and Newtonia, 1672–1975: a bibliography*, published at Folkestone in 1977, provides a pageant of over 5000 books and articles over three centuries; this replaces J.G. Gray's *A Bibliography of the Works of Sir Isaac Newton* (Cambridge, 1907). Henry P. Macomber has published 'A census of copies of the 1687 first edition and the 1726 presentation issue of Newton's Principia' in *Bibliographic Society of America*, 47 (1953), 269–300;[11] while the critical reproduction of the third edition (1726) of *Philosophiae naturalis principia mathematica* assembled and edited by Alexander Koyré and I. Bernard Cohen (2 vols, Cambridge, Mass., 1972) includes an annotated bibliography of the work's complete and partial editions, both in Latin original, and in English, French, German, Italian, Japanese, Rumanian, Russian and Swedish translations. Finally, Newton scholarship is beholden to *A Descriptive Catalogue of the Grace K. Babson Collection of the Works of Sir Isaac Newton and the Material Relating to him in the Babson Institute Library, Babson Park, Mass.* (New York, 1950).

Robert Hooke, Newton's rival and *bête noir*, has been treated by Geoffrey Keynes in *A Bibliography of Robert Hooke* (Oxford, 1960). One important eighteenth-century itinerant lecturer and instrument makes has also received bibliographical treatment. This is J.R. Millbourne, *A Bibliography of James Ferguson, FRS (1710–1776)* (Aylesbury, 1983). Alan Jeffreys, *Michael Faraday, a list of his lectures and published writings* (London, 1960), is somewhat out of date, given the revival of interest in Faraday during the last 30 years, but is indispensable. Over 1000 publications of Sir David Brewster are listed by Alison Morrison-Low in her *Martyr of Science. Sir David Brewster 1781–1868*, co-edited with J.R.R. Christie, and published by the Royal Scottish Museum at Edinburgh, 1984. Bibliographies of other physicists are best retrived from individuals' *DSB* entries. The History of Science Department at Berkeley, California has published a number of short bibliographies of the 'non-technical' writings of eminent physicists, including Max Planck (1977), William Henry Bragg and William Lawrence Bragg (1978), and Ernest Rutherford (1979). Mainly to emphasize his spiritualistic writings, Theodore Besterman compiled *A Bibliography of Sir Oliver Lodge, FRS* (London, 1935). Finally, Albert Einstein has

attracted two bibliographers: Nell Boni, M. Ross and D.H. Laurence (eds), *A Bibliographical Checklist and Index to the Published Writings of Albert Einstein* (Paterson, New Jersey, 1960); E. Weil, *Albert Einstein – 14th March 1879 (Ulm)–18th April 1955 (Princeton, New Jersey): a bibliography of his scientific papers 1901–1954* (London, 1960).

Chemistry

Any research in history of chemistry must begin with J.R. Partington, *A History of Chemistry* (4 vols, London, 1961–70). Although an expository (and encyclopaedic) text, it is based upon an intimate acquaintance with chemical literature and abounds with bibliographical information.[12] Partington's own remarkable collection of historical material was given to the University of Manchester.

Chemistry has always been well served bibliographically since the time of Elias Ashmole (1617–92),[13] the antiquary, astrologer and alchemist. His *Theatrum Chemicum Britannicum; containing severall poetical pieces of our famous English philosophers* (London, 1652), consists of a number of old English poems on alchemy, with notes by Ashmole. Only the first part was published, and the work is very rare, but it was reprinted with a new introduction by Allen G. Debus (New York, 1967); and with a preface by G. Heyer and J.M. Watkins (Hildesheim, 1967). The next chemical bibliography emanated from France, where its author, a medical man, was physician to the King. Pierre Borel (1620–71 or 1689) was the author of numerous books, many of which he left in manuscript, and he was keenly interested in natural history, astronomy, bibliography and antiquities. His *Bibliotheca Chemica, seu catalogus liborum philosophicorum hermeticorum in quo quatuor millia circiter authorum chimicorum ... quam in lucem editorum, cum eorum editionibus jusque ad annum 1653 continentur* (Paris, 1654) lists 4000 items devoted to alchemy, and was reprinted at Heidelberg in 1656.

William Cooper, a bookseller at the sign of the Pelican in Little Britain, London, during the latter half of the seventeenth century, specialized in alchemical literature, writing and publishing several works on the subject. He compiled *A Catalogue of Chymicall Books ... written originally, or translated into English* (London, 1675), which has been described by Ferguson (vol. 1, p. 135, below) as 'an advance in detail and precise information on Borel's *Bibliotheca*'. It has been reprinted, with an analytical introduction by Stanton J. Linden (New York and London, 1987).

As an example of the *Bibliothecae*, which generally consist of reproductions of texts rather than mere lists, we mention one of the many similar works compiled by Jean Jacques Manget (1652–1742). His *Bibliotheca chemica curiosa, seu rerum ad alchemiam pertinentium thesaurus instructissimus* (2 vols, Geneva, 1702) reproduces 170 tracts on the subject, many of these being extremely rare. A further bibliography of alchemical literature is contained in Nicolas Lenglet

Du Fresnoy's *Histoire de la philosophie hermétique. Accompagnée d'un catalogue raisonné des écrivains de cette science* (vol. 3, Paris 1742, and The Hague, 1744; Paris, 1744), listing 1500 items. Du Fresnoy (1674–1752) wrote extensively on historical subjects, the first two volumes of this work being of that nature. He disbelieved in alchemy, and his work is severely critical. Works on alchemy contained in the British Library collections have been listed by Kurt Karl Doberer in *A bibliography of books on Alchemy in the British Museum*, 1946. Other collections include Ron. Charles Hogart (ed.), *Alchemy. A comprehensive bibliography of the Manly P. Hall Collection of books, manuscripts including related materials on Rosicrucianism and the writings of Jacob Boehme* (Los Angeles, 1986); and another by Ian MacPhail (ed.), *Alchemy and the Occult. A catalogue of books and manuscripts from the collection of Paul and Mary Mellon given to Yale University Library* (2 vols, New Haven, 1968). In addition to collations and tabulations of the contents of 160 imprints, there are full accounts of illustrations, decorations, typography, paper and binding.[14] Esoteric writings on alchemy are cited extensively in A.L. Caillet, *Manuel bibliographique des sciences psychiques ou occultes* (3 vols, Paris, 1912). A very useful general guide to alchemical works in the English language is R. Pritchard, *Alchemy. A bibliography of English-language writings* (London and Boston, 1980). This contains more than 3400 references and includes texts and secondary works, including theses, written between 1597 and 1978. Pritchard sensibly includes subjects that influenced alchemical thought, such as astrology, gnosticism and Neoplatonism. Claudia Kren, *Alchemy in Europe. A guide to research* (New York and London, 1990), includes 520 works written in or translated into English. The annotations are good but the book is poorly proof-read.

Johann Wilhelm Baumer (1719–88) was the author of *Bibliotheca chemica* (Giessen, 1782), a 'brief but useful bibliography,' containing some 750 entries. Baumer was a professor of medicine who wrote extensively on his own subject and on minerals and geology, as well as a *Fundamenta chemicae theoretico-practicae* (Giessen, 1783). Another professor of medicine, Georg Friedrich Christian Fuchs (1760–1813), a native of Jena, published numerous chemical papers, and was the author of a *Repertorium der chemischen Literatur von 494 vor Christi geburt bis 1806 ... von den Verfassern des systematischen Beschreibung aller Gesundbrunnen und Bäder in und ausser Europa*. This appeared in four volumes (Jena and Leipzig, 1806–12) and was reprinted in two volumes (Hildesheim and New York, 1974).

One of the most comprehensive bibliographies of chemistry, and still extraordinarily useful, is that by Henry Carington Bolton (1843–1903) entitled *A Select Bibliography of Chemistry, 1492–1892* (Washington, 1893) and published by his employers, the Smithsonian Institution. A reprint was published in 1966. The main work contains 12,031 titles, and there are two supplements, the first, published in 1899, covering the years 1492–1897, and listing 5554 entries; the second, covering 1492–1902, was published in 1904. The work is devoted to independent works; there is a biographical section, and lists of obituaries from

selected periodicals. It is altogether divided into seven sections: bibliography, dictionaries, history, biography, chemistry (pure and applied), alchemy, and periodicals. There is also a subject index. Section 8 of the work, devoted to the world's academic dissertations, was published separately in 1901. Bolton's amazing industry is now valuably complemented by Valentin Wehefritz and Zoltan Kovats (eds), *Bibliography on the History of Chemistry and Chemical Technology 17th to the 19th Century* (3 vols, Munich, 1994). The first volume of this production lists subjects chronologically; the second and third volumes arrange literature by chemists. There are altogether 25,000 entries. In addition, the historian of chemistry and of the chemical industry will find useful Robert P. Multhauf, *The History of Chemical Technology. An annotated bibliography* (New York, 1984).

The best-known bibliography devoted to a library of chemical literature is the catalogue of a private collection, compiled by an academic chemist who himself acquired a notable library. James 'Paraffin' Young (1811–83) was a native of Glasgow, and became the founder of the paraffin oil industry in Scotland. His collection of books is in the University of Strathclyde, Glasgow, and the catalogue of it was compiled by John Ferguson as *Bibliotheca Chemica; a catalogue of the alchemical, chemical and pharmaceutical books in the collection of the late James Young* (2 vols, Glasgow, 1906). Although printed for private distribution by Young's family in accordance with his instructions, the work rapidly acquired importance amongst bibliophiles and dealers. It was reprinted in 1954. It is in alphabetical order by author, full annotations providing valuable biographical information and references as sources of additional information. Ferguson (1837–1916) was Regius Professor of Chemistry in the University of Glasgow from 1874 to 1915,[15] and was the author of several other bibliographical works, including *Bibliotheca Paracelsica*, in six parts (1877–96) and a series of papers initially prepared for the Glasgow Archaeological Society and published in Glasgow (1896–1915) which were reprinted in collected facsimile as *Bibliographical Notes on Histories of Inventions and Books of Secrets* (2 vols, London, 1959). Himself no mean book collector, his fine collection of books were sold in Glasgow (June 1920), and at Sotheby's (November, 1920), the remainder being purchased by the University of Glasgow. These number about 6000 volumes. A two-volume catalogue, edited by Katherine R. Thomson and Mary Margaret Service, and edited by William Ross Cunningham was printed in Glasgow, 1943, as *Catalogue of the Ferguson Collection of Books, mainly relating to Alchemy, Chemistry, Witchcraft and Gipsies, in the Library of the University of Glasgow.*

The Young collection is rich in sixteenth- and seventeenth-century items, and a companion bibliography supplementing this by its eighteenth- and nineteenth-century material must be mentioned here. This is Dennis I. Duveen (d. 1995), *Bibliotheca alchemica et chemica. An annotated catalogue of printed books on alchemy, chemistry and cognate subjects in the library of Dennis I. Duveen* (London, 1949), of which a second edition was published in 1965. The collec-

tion, minus all the Lavoisier items, is now in the University of Wisconsin. This *Bibliotheca* was first printed in a limited edition of 200 copies, of which ten were on hand-made paper and not for sale. It is arranged alphabetically by authors, entries being annotated. There is no bibliographical information, or even bare dates of birth and death of authors, but under authors' names entries are chronologically arranged. Sixteen collotype plates are included, 3000 items being listed. The whole collection was subsequently included, with additions, in *Chemical, Medical and Pharmaceutical Books printed before 1800. In the collection of the University of Wisconsin libraries*, and edited by John Neu from the compilation work of Samuel Ives, Reese Jenkins and John Neu (Madison and Milwaukee, 1965). Another important bibliophile of history of chemistry is William Cole. His *Chemical Literature 1700–1860. A bibliography with annotations, detailed descriptions, comparisons and locations* (London and New York, 1988), also provides a brief history of chemical bibliography.

Duveen's remarkable collection of the works of Antoine Laurent Lavoisier (1743–94) were acquired by the Olin Library of Cornell University. Duveen collaborated with H.S. Klickstein on *A Bibliography of the Works of Antoine Laurent Lavoisier, 1743–1794* (London, 1954); Duveen alone produced a further *A Supplement to a Bibliography of the Works of Antoine Laurent Lavoisier*, which was published in London, 1965, bringing the literature up to 1963. Patrice Bret has added a very useful bibliography, arranged chronologically, of books and articles about Lavoisier published since 1963. This appears in a special issue of *Revue d'histoire des sciences*, 48 (January–June 1995) entitled *Débats et chantiers actuels autour de Lavoisier et la révolution chimique*. Bret's work advantageously adds an author index to both his own and to Duveen's work. Lavoisier studies have been further enhanced by Ferdinando Abbri and Marco Beretta's 'Bibliography of the *Méthode de nomenclature chimique* and of the *Traité élémentaire de chimie* and their European translations (1787–1800)', which is to be found in Bernadette Bensaude-Vincent and Ferdinand Abbri (eds), *Lavoisier in European Context. Negotiating a new language for chemistry* (Canton, MA, 1995). This covers France, Italy, Spain, Portugal, Great Britain, the German states (including Austria), The Netherlands, Sweden and Denmark. Lavoisier's own library has been reconstructed by M. Beretta in *Bibliotheca Lavoisieriana. The catalogue of the library of Antoine Laurent Lavoisier* (Firenze, 1995).

Probably because chemists tend to publish much more than other scientists, several other important chemists have been given bibliographical treatment, notably, Boyle, Black, Priestley, Dalton, Davy, Berzelius and Liebig. The distinguished physician and bibliographer, John F. Fulton, published *A Bibliography of the Honourable Robert Boyle* (2nd edn, Oxford, 1961); Michael Hunter, ed., *Robert Boyle Reconsidered* (Cambridge, UK, 1994), lists about 300 publications on Boyle written since 1940; J.G. Fyffe and R.G.W. Anderson have compiled *Joseph Black: a bibliography* (London, 1992) which includes 92 items by Black, 70 works by Black's contemporaries in which his work is discussed, 45 publica-

tions concerned with the controversy over causticity, and 360 works about Black published between 1764 and 1986. A valuable iconography of Black is also included. Ronald E. Crook, *A Bibliography of Joseph Priestley, 1733–1804* (London, 1966), demonstrates the catholicity of interests of this theologian-natural philosopher and educator. A.I. Smyth, *John Dalton, 1766–1844. A bibliography of works by and about him* (Manchester, 1966; revised and enlarged, Aldershot, 1998) is still useful. J.Z. Fullmer, *Sir Humphry Davy's Published Works* was published in Cambridge, MA, in 1969. Davy's Swedish rival, Jöns Jacob Berzelius, has been handsomely treated by Arne Holmberg in *Bibliografi över J.J. Berzelius* (5 parts, Stockholm, 1933–36), with a further *Supplement* in 1953. Carlo Paoloni, *Justus von Liebig. Eine Bibliographie sämtlicher Veröffentlichungen* (Heidelberg, 1968), despite some infelicities, is indispensable for the study of this remarkable chemist. Its 990 entries were continued by the industrial chemist Emil Heuser (1918–95), who before his death had accumulated 8106 entries. This impressive holograph bibliography is probably unpublishable but xerox copies, housed in eight volumes, have been deposited in a number of libraries and centres, including the Justus Liebig Gesellschaft at Giessen, the Liebigiana Collection of the Staatsbibliothek at Munich, the Göttinger Chemische Gesellschaft Museum, the Library of the Berzelius Society in Stockholm, and the Chemical Heritage Foundation, Philadelphia. Theses submitted by Liebig's British and American pupils, as well as those of other German chemists, can be traced in Paul R. Jones, *Bibliographie der Dissertationen amerikanischer und britischer Chemiker an deutschen Universiäten 1840–1914* (Munich, 1983).

Some booksellers' catalogues can be of bibliographical interest, and one in the field of history of chemistry has assumed the role of becoming a permanent bibliography. Henry Sotheran's *Bibliotheca chemico-mathematica: a catalogue of works in many tongues on exact and applied science, with a subject index* (2 vols, London, 1921) was compiled and annotated with the help of H. Zeitlinger. It was begun in 1906 as the catalogue of a large collection of books for sale, but grew into five volumes containing 47,490 items covering astronomy, chemistry, mathematics, physics and allied subjects. Volume 1 is alphabetical, with a supplement A-GILL; volume 2 continues this alphabetical sequence, and after brief 'further addenda', proceeds to a further 'final supplement' which is classified, and completed by a subject index. The first supplement (1932), the second (two volumes), and the third (1952), are classified under broad headings, and then arranged alphabetically by authors. Although lacking an author index, throughout the work bibliographical and historical notes, facsimiles, portraits and contemporary prices are provided.

Periodically published bibliographies of chemistry that are of importance to historians include Jacob Berzelius' *Jahresbericht über die Forschritte der physischen Wissenschaften* in 20 volumes (Tübingen, 1822–41), which was continued by a consortium of German chemists as *Jahresbericht über die Fortschritte der Chemie und Mineralogie*, volumes 21–29 (1842–50). A further

series of *Jahresbericht über die Fortschritte der reinen, pharmaceutischen und technischen Chemie, Physik, Mineralogie und Geologie* began surveying the literature from 1847 and was published from various German university towns from 1849 until 1913. The French equivalent survey is the *Répertoire de chimie pure et appliqué*, that was published by the Société chimique de Paris between 1863 and 1906. Both these German and French series are indispensable for the period before the appearance of *Chemical Abstracts* published by the American Chemical Society since 1907. Also useful is the *Pharmaceutische Zentralblatt* (1830–1849), when it became *Chemisch-Pharmaceutisches Centralblatt.* This was acquired by the Deutsche Chemische Gesellschaft in 1897, when it assumed the modern title *Chemisches Zentralblatt: vollständiger Repertorium für aller Zweige der reinen und angewandten Chemie*, which ceased formal publication in this form in 1969. Like organic chemists, historians of chemistry also need to be familiar with the still continuing *Handbuch der organischen Chemie* founded by Friedrich Konrad Beilstein (1838–1906). The first edition appeared in two volumes (1881–82) and surveyed the literature on 15,000 carbon compounds. Further editions appeared between 1885–89 and 1892–1906. The fourth edition, which is the one most familiar to historians and chemists, has been kept in print and updated since it was begun in 1918. A basic series of 27 volumes (H, Hauptwerk) covers literature published before 1909, while supplementary series, each of 27 volumes (E, Ergänzungswerk) survey decades of material 1910–1919, 1920–29, etc.[16] Beilstein has appeared in English since the first supplementary series began in 1984. Pharmacy is covered in Gregory J. Higby and Elaine C. Stroud, eds, *The History of Pharmacy: a selected annotated bibliography* (New York, 1995).

Photography was a chemical science during its early period of development. Laurent Roosens and Luc Salu, *History of Photography. A bibliography of books* (London, 1995) aims to be comprehensive for the period up to 1914, and offers selective treatment from that date. About 11,000 books are grouped under 3000 alphabetically arranged subject headings. There is also a comprehensive names index.

The eminent biochemist, Joseph S. Fruton (1912–), has devoted much attention to forwarding the history of his subject. His *A Bio-Bibliography for the History of the Biochemical Sciences since 1800* (Philadelphia, 1982) generated a *Supplement* in 1985. These are now amalgamated in a revised second edition (Philadelphia, 1995). Fruton's eclecticism means that chemists whose work was only peripheral to physiological chemistry are also included. The work thereby complements the bibliography of Wehefritz and Kovats.

Geology

Geology and mineralogy are catered for by the following bibliographical tools, listed briefly: William A.S. Sarjeant, *Geologists and the History of Geology* is an

international bibliography from the origins of the science to 1878, which was published from typescript at Basingstoke, 1980, and reissued in 1986. There are five substantial volumes. The first introductory volume includes accounts of societies, museums and the development of the petroleum industry; the second and third volumes list bibliographies of individual geologists; the fourth volume is an index of geologists by nationality, country and specialism; and the final volume indexes authors, editors and translators. The set contains some 6893 items and indexes about 30,000 works. Two supplementary volumes covering the secondary literature from 1979–84 were published at Malibar, Florida, in 1987. A further three volumes, defined as Supplement II (1985–93) were published by Krieger at Melbourne, Florida, in 1996. This magnificent bibliography has been hailed as a landmark reference tool in the history of geology and replaces much, if not most, earlier twentieth-century bibliographical material. For a short, succinct guide to geological literature, however, attention must also be drawn to Roy Porter, *The Earth Sciences. An annotated bibliography* (New York, 1983) which has 808 citations selected from the secondary literature.

Among pre-twentieth-century bibliographical material, mention should be made of Carl Friedrich Wilhelm Schall's *Oryktologische Bibliothek* (Weimar, 1787), that lists 1500 items. It was followed by a second edition bearing the title *Anleitung zur Kenntniss der besten Bücher in der Mineralogie und physikalischen Erdbeschreibung* (Weimar, 1789) which contains about 70 extra items. Christians Keferstein's *Geschichte und Literatur der Geognosis* (Halle, 1840) and J.D. Dana's *Bibliography of Mineralogy,* published in 1881, are still useful historical sources.

An important list of nearly 4000 bibliographies of geology published between 1726 and 1895 exists in Emmanuel de Margerie's *Catalogue des bibliographies géologiques* (Paris, 1896). This is in three parts, the first dealing with general bibliographies, the second with bibliographies of special subjects, while the third lists personal bibliographies and obituaries. An author index is provided. This work was supplemented by Edward B. Mathews' *Catalogue of Published Bibliographies in Geology, 1896–1920* (Washington, 1923), which is arranged in the same way and contains 3699 titles. An important guide to geological maps was published by A. Morley Davies as *Local Geology; a guide to sources of information on the geology of the British Isles* (London, 1927). The literature of North America is covered by John Milton Nickles' *Geological Literature of North America 1785–1928*, three volumes (*US Geological Survey Bulletins 746, 747 and 823*), 1923–31, continued in biennial supplements as *Bibliography of North American Geology, 1929–30*, etc.

Among the most interesting of the *Bibliothecae* for history of geology is D.C. Ward and A.V. Carozzi (eds), *Geology Emerging. A catalog illustrating the history of geology (1500–1850) from a collection in the library of the University of Illinois at Urbana-Champaign* (Urbana-Champaign, Illinois, 1984) which forms part of the 11-volume catalogue of this university library issued between 1972 and 1984. A reference library made by Herbert Clark Hoover (the later President

of the United States of America) and his wife, Lou Henry Hoover, when they were preparing their translation of Agricola's *De re metallica* (1556) in 1912 was deposited in the Norman F. Sprague Memorial Library of Harvey Mudd College, Claremont, CA in 1970. A catalogue of the 912 mining and metallurgical books in the collection, *The Bibliotheca De Re Metallica*, was published by the Claremont Colleges in 1980, with annotations by David Kuhner and Tania Rizzo, with an introduction by the historian of metallurgy, Cyril Stanley Smith.

Individual geologists have not attracted the attention of bibliographers in the way that natural philosophers and natural historians have done, and resort to the *DSB* must be made. The publication history of Charles Lyell's *Principles of Geology* is analysed in Derek Gjertsen's *The Classics of Science* (New York, 1984); while the writings of the Scots stonemason geologist, Hugh Miller (1802–56), have been listed by Michael Shortland in his *Hugh Miller's Memoir: from stonemason to geologist* (Edinburgh, 1995).

Biology

The history of biology is a vast subject; for the purposes of this chapter we have grouped together bibliographies devoted to general biology, zoology and botany, but ignored natural history except where it influenced the course of science directly. The many highly specialized and fascinating bibliographies of ornithology, ichthyology and entomology are also passed over. Such bibliographies are easily identified through the bibliography with which all literature searching should begin: Gavin D.R. Bridson, *The History of Natural History. An annotated bibliography* (New York, 1994), the largest and best of the Garland Bibliographic Series. Bridson's knowledge of the field is impeccable having trained as an antiquarian bookseller, served as Librarian and Archivist of the Linnean Society, and acted as a Bibliographer at the Hunt Institute for Botanical Documentation. The study lists some 7500 books and articles published worldwide before 1992, covering the period from the fifteenth to the twentieth century. Also extremely useful is Pieter Smit, *History of the Life Sciences. An annotated bibliography* (Amsterdam, 1974), which was started initially as a continuation of the biological entries in Sarton's *Horus*. It has some 4000 entries each with full bibliographic information on author, title, date, edition, collation, etc. The four parts deal with general references and tools, the historiography of the life and medical sciences, the historiography of the same from the Renaissance onwards, and a selected list of biographies and bibliographies of the most important biological investigators. For a guide to the most recent history of biology literature, Judith A. Overmier, *The History of Biology. A selected, annotated bibliography* (New York, 1989) should be consulted. This contains 620 entries. L'Académie des Sciences de l'Institut de France, *Histoire et Nature. Introduction bibliographique à l'histoire de la biologie* (Paris, 1975) has been largely superceded by Bridson, Smit and Overmier.

Three guides to the early literature of natural history are of special interest. Firstly, Johann Ludwig Choulant (1791–1861), the author of several medical bibliographies, compiled *Graphische Incunabeln für Naturgeschichte und Medizin* (Leipzig, 1858; facsimile reprint, Munich, 1924). This list of illustrated incunabula is not exhaustive, but provides complete bibliographical details, with particulars of place of publication, date, size, name of printer, month, and annotation. The second, although only a typescript thesis,[17] is worthy of mention. It is by Catherine H.W. Bickle, and entitled *A Bibliography of Zoological Works, by British authors or printed in Great Britain, 1477–1550* (1948). There are some collations, useful annotations, locations of copies, STC references, an index of printers, and a general index. The bibliographer, R.B. Freeman, has also compiled the useful *British Natural History Books, 1495–1900. A handlist* (Folkestone, 1980) which is an alphabetical list of over 4000 volumes.

Bibliographies of individual biologists are uncommon. Most notable, inevitably, is R.B. Freeman, *The Works of Charles Darwin: an annotated bibliographical handlist* (2nd edn, Folkestone, 1977). A list of the published writings of Darwin's polymath cousin, Francis Galton, is given in D.W. Forrest, *Francis Galton. The life and work of a Victorian genius* (New York, 1974). Linnaeus's publications are surveyed in J.M. Hulth, *Bibliographica Linneania* (Uppsala, 1907); and those of the eminent seaside naturalist, Philip Gosse, in R.B. Freeman and D. Wertheimer, *P. H. Gosse. A bibliography* (Folkestone, 1980). Attention must also be drawn to Geoffrey Keynes, *John Ray, a bibliography* (London 1951; 2nd enlarged edn, Amsterdam 1974). A helpful, though partial guide to the prolific writing s of Thomas H. Huxley, is found in Mario di Gregorio, *T. H. Huxley's Place in Natural Science* (New Haven, 1984). More generally, books and articles on significant nineteenth-century naturalists and biologists are listed regularly in the annual bibliography of the journal *Victorian Studies*. Articles which make literary and cultural connections will here be to the forefront.

Eighteenth-century bibliographies that retain their value are Johann Jacob Scheuchzer's (1672–1733) *Bibliotheca scriptorum historiae naturalis ... de scriptoribus historiae naturalis Galliae* (Zürich, 1716; reissued in 1751). Scheuchzer was also the author of *Helvetiae historia naturalis* (three parts, Zürich, 1716–18) which is in Latin and German. F.C. Bruckmann's *Biblioteca animalis* was published at Wolfenbüttel in 1743, and was followed by Laurenz Theodor Gronovius' (1730–77) *Bibliotheca regni animalis atque lapidei, seu recensio auctorum et liborum, qui de regno animali et lapideo ... tractant* (Leyden, 1760), a rare work listing 5000 entries. Gronovius published his *Zoophylacium* in parts, 1763–81,[18] and was also the author of *Museum ichthyologicum* (2 vols, Leyden, 1754). Georg Rudolph Boehmer compiled the *Bibliotheca scriptorum historiae naturalis, oeconomiae aliarumque artium ac scientiarum as illam pertinentium realis systematica* (9 vols, Leipzig, 1785–89), which has 65,000 entries.

The greatest bibliography of natural history published in the nineteenth century was begun by the prolific bibliographer, Wilhelm Engelmann (1808–

78). His *Bibliotheca Historico-Naturalis. Verzeichniss der Bücher über Naturgeschichte welche in Deutschland, Scandinavien, Holland, England, Frankreich, Italien und Spanien in den Jahren 1700–1846 erschienen sind*, was published at Leipzig in 1846, and was reprinted in 1960. This first volume contains 10,000 entries, and was followed by a supplementary volume by J. Victor Carius and Wilhelm Engelmann bearing the title *Bibliotheca zoologica. Verzeichniss der Schriften über Zoologie welche in den periodischen Werken enthalten, und vom Jahre 1861–1880 Selbständig erschienen sind* (2 vols, Leipzig, 1861). This lists another 40,000 items, and was in turn continued in a work by Ernst Otto Wilhelm Taschenberg (1854–1928) entitled *Bibliotheca zoologica II*, with the same subtitle, but referring to the years 1861–80. This appeared in seven volumes (in eight) at Leipzig, 1886–1930. The volumes forming this exhaustive bibliography are classified, with both author and subject indexes.

Louis Jean Rodolphe Agassiz (1807–73) was the author of numerous books on zoological and geological topics, but his bibliographical effort is not as valuable as the names of the author and the publishers, the Ray Society, might suggest. It is not selective, the entries are very brief, and there are no annotations. Entitled *Bibliographia Zoologiciae et Geologiae. A general catalogue of all books tracts and memoirs on zoology and geology, corrected, enlarged and edited by H. E. Strickland (volume four ... and Sir William Jardine)* (4 vols, London, 1848–54; reprinted New York, 1968), this includes articles in journals. Volume 1 lists periodicals by country, and includes authors A–B; the three other volumes complete the alphabet, listing a total of 40,000 items. Despite its inadequacies this is an important source-book for tracing the early literature. It lists the various editions and translations of items recorded, and the first volume contains an extensive list of sources consulted in the preparation of the bibliography.

The following two items are particularly specialized, but are of outstanding importance in their respective classes. Max Meisel's *A Bibliography of American Natural History. The pioneer century, 1769–1865* (3 vols, Brooklyn, 1924–29; reprinted New York, 1967), covers almost a century of important literature. It is the best source of information on the history and early publications of state geological surveys, of scientific societies and journals, and contains a bibliography of biographies. *A Bibliography of Eugenics*, by Samuel Jackson Holmes (born 1868), was issued in the University of California's Publications in Zoology series (volume 25, 1924, pp. 1–514). The subject has attracted historians in large numbers since the 1960s, but no continuation of Holmes has been attempted.

One of the most important bibliographies of zoology is *An Introduction to the Literature of Vertebrate Zoology based chiefly on the titles in the Blacker Library of Zoology, the Emma Shearer Wood Library of Ornithology, the Bibliotheca Osleriana, and other libraries of McGill University, Montreal* (London, 1931), compiled and edited by Casey Albert Wood (1856–1942). This contains an extensive historical introduction consisting of chapters devoted to chronological periods, to particular branches of the subject, and to specialist

material, such as periodicals, rare books, manuscripts, etc.; a chronological list of publications; and an alphabetical catalogue, arranged chronologically under names of authors. This bibliography lists about 15,000 works, and contains useful annotations. Another 60,000 volumes are recorded in *A Dictionary Catalogue of the Blacker-Wood Library of Zoology and Ornithology* (9 vols, Boston, 1966). Claus Nissen has published two volumes entitled *Die zoologische Buchillustration: ihre Bibliographie und Geschichte* (Stuttgart, 1968–78). Nissen has also contributed an historical and bibliographical text to an edition limited to 100 copies of *Tierbuecher aus 5 Jahrhunderten. 58 Originalblätter aus zoologischen Prachtwerken von 1491 bis 1905* (Munich, 1967).

The Society for the Bibliography of Natural History was founded in 1936 and renamed the Society for the History of Natural History in 1983. Its *Journal* (now the *Archives of Natural History*) contains a good deal of valuable specialized and even arcane bibliographical information, for example, on the dates of publication of natural history books,[19] or ones on whaling,[20] and of the Sowerby family of naturalists and illustrators.[21] David Knight's *Natural Science Books in English, 1600–1900* (London, 1972), and *Zoological Illustration. An essay towards a history of printing zoological pictures* (Folkestone, 1977), while not conventional bibliographies, are also useful introductions to the graphic contents of biological books. However, the first port of call is undoubtedly to Gavin D.R. Bridson and James J. White, *Plant, Animal and Anatomical Illustration in Art and Science. A bibliographic guide from the sixteenth century to the present day* (Detroit, 1990). Jessie Craft Ellis's compilation, *Nature and its Applications: over 200,000 selected references to native forms and illustrations of nature as used in every way* (Boston, 1949), enables references to more popular articles on natural history to be traced and to find requisite illustrations.

Although the title of the next historical work suggests that it is confined to literature on the primates, many of the entries are concerned with zoology in general. Theodor C. Ruch's *Bibliographia primatologica: a classified bibliography of primates other than man. Part I. Anatomy, embryology & quantitative morphology; physiology, pharmacology & psychobiology; primate phylogeny & miscellanea* (Springfield, Baltimore, 1941) was issued as Publication No. 4 of the Historical Library, Yale Medical Library, and lists material published up to 1939. The first three sections deal with the knowledge of primates in the ancient world and the Middle Ages, the sixteenth and seventeenth centuries, and the eighteenth century respectively, these sections being arranged alphabetically by authors. The remainder of the work is classified, with an author index. Full names of authors, with dates of birth and death, are provided, and there are 4630 entries.

Periodical bibliographies covering this field include *Jahresbericht über die Fortschritte in der Biologie*, published at Erlangen from 1843 to 1850 (frequently referred to as Constatt's *Jahresbericht*); *The Record of Zoological Literature*, volumes 1–6 (1864–99), which was continued as *The Zoological Record*, volume 7 (1870 onwards), and is published by the Zoological Society

of London. Its history has been reviewed by G.D.R. Bridson.[22] There have been comparable French and German indexes to periodical articles, but *The Zoological Record* will suffice for most purposes.

Some help with research on oceanographic topics is supplied by *Selected References to Literature on Marine Expeditions 1700–1960* (Boston, MA, 1972), an unedited compilation of 9000 card references to oceanographic research located in the Fisheries-Oceanographic Library of the University of Washington.

Finally, *A Guide to the History of Bacteriology* by Thomas H. Grainger (New York, 1958), provides a guide to the literature on bacteriology. Part 1 in 31 sections covers very widely the bibliography of science and medicine inasmuch as bacteriology is included. Part 2 deals with the history of bacteriology and provides a detailed bibliography of books, chapters in books, and articles; Part 3 provides biographical references in general; and part 4 is a selective guide to biographies of bacteriologists arranged alphabetically, and including details of biographies, collected works, letters, etc.

Botany

A comprehensive bibliography of bibliographies of botany up to 1909, compiled and annotated by Jens Christian Bay,[23] was published under the title 'Bibliographies of botany. A contribution towards a bibliotheca bibliographica' in *Progressus rei botanicae*, vol. 3 (1910), pp. 331–456. Entries are arranged in 12 groups and, unusually, lists auction and sales catalogues of private libraries and booksellers' catalogues.

The first attempt at a complete bibliography of botany, both manuscripts and printed books, was the *Bibliotheca botanica seu Herboristarum Scriptorum promota synodia, cui accessit individualis graminum omnium ab auctoribus hujusque observationum numerosissima nomenclatura. Io. Antonio Bumaldo collectore* (Bologna, 1657). Bumaldus is an anagram of the author's name, the work being by Ovidio Montalbani. It is chronologically arranged, but the work is very rare in this edition. However, it was subsumed in Jean François Seguier's *Bibliotheca botanica, sive catalogus auctorum et liborum omnium qui de re botanica*, published a century later at The Hague, 1740. A supplement was published at Verona, 1745, and a further supplement at Leyden, 1760.

Albrecht von Haller (1708–77) has been described as the founder of medical and scientific bibliography by Sir William Osler. He was professor of anatomy, botany and surgery at the University of Göttingen, and wrote extensively on these subjects. Haller was also responsible for several extensive bibliographies, including *Bibliotheca anatomica* (2 vols, Zürich, 1774–77). His *Bibliotheca botanica* (2 vols, Zürich, 1771–72) is similarly arranged into sections representing the historical periods of botany, and subdivided by authors, with information on their lives, writings and various editions, and notes on the contents of books. An *Index emendatus to [Haller's] Bibliotheca botanica* was prepared by Jens

Christian Bay, and published in Berne, 1908. A reprint of Haller's original bibliography was published in two volumes (Bologna, 1966).

Several other German bibliographies of botany followed Haller's, including *Über Literargeschichte der theoretischen und praktischen Botanik* (Marburg, 1794) by Ernst Gottfried Baldinger (1738–1804); and J.A. Schultes' *Grundriss einer Geschichte und Literatur der Botanik von Theophrastos Eresios bis auf die neusten Zeiten* (Vienna, 1817), which lists 2500 items; Friedrich von Miltitz's *Handbuch der botanischen Literatur für Botaniker, Buchhändler, und Auctionatoren* (Berlin, 1829), containing some 5000 items; and Marcus Salomon Krüger's *Bibliographia botanica. Handbuch der botanischen Literatur* (Berlin, 1841), with 10,000 entries.

Georg August Pritzel's *Thesaurus literaturae botanicae omnium gentium inde a rerum botanicarum initiis as nostra jusque tempora, quindecim millia operum recens* (Leipzig, [1847]–1851), was issued in parts. Part I is arranged alphabetically by authors, with a appendix of anonymous works, and part 2 is classified, with an author index. Additions to this bibliography were published in 1853, 1859, with an index 1862–64, and a new edition was published at Leipzig, 1872–77 (reprinted Milan, 1950). Pritzel is complemented by Benjamin Daydon Jackson's *Guide to the Literature of Botany; being a classified selection of botanical works, including nearly 6,000 titles not given in Pritzel's 'Thesaurus'* (London, 1881; reprinted New York, 1964). This contains nearly 9000 short-title entries, with an author index arranged under bibliography; history; biography, encyclopaedias; systems; pre-Linnean botany, etc. Blanche Henrey's elegantly printed *British Botanical and Horticultural Literature before 1800* (3 vols, Oxford, 1975) is another useful point of entry for research and is particularly valuable for information concerning historical publications on botanical gardens and seedsmen.

Other bibliographies that offer useful information for historians, despite being originally designed for practising botanists, are: H. Trimen, *Botanical Bibliography of the British Counties* (London, 1874); *Index Kewensis: an enumeration of the genera and species of flowering plants, from the time of Linnaeus to the year 1885 inclusive, together with their authors' names, the works in which they were first published, their native countries and their synonyms. Compiled at the expense of the late Charles Robert Darwin under the direction of Sir J. D. Hooker. By B. D. Jackson*, two volumes in four (1895), the title of which is explanatory, and to which 14 supplements were published between 1901 and 1979 (reprinted Koenigstein, 1978–79, and microfiche edition, 1983). The work continues as *Kew Index*. Alfred Rehder's *The Bradley Bibliography: A guide to the literature of the woody plants of the world published before the beginning of the twentieth century* (5 vols, Cambridge, Mass., 1911–18), was compiled at the Arnold Arboretum of Harvard University. This covers arboriculture, forestry etc., and there are indexes of authors and titles. A fifth volume is a supplement containing additions and corrections to the first four volumes. A list of over 20,000 figures of flowers is contained in *Index*

Londinensis, to illustrations of flowering plants, ferns and fern allies. Being an amended and enlarged edition continued up to the end of the year 1920 of Pritzel's Alphabetical Register of representations of flowering plants and ferns. Compiled from botanical and horticultural publications of the XVIIIth and XIXth centuries. This was prepared at Kew Gardens by O. Stapf under the auspices of the Royal Horticultural Society of London, in six volumes, 1929–31, to which a two-volume supplement covering the years 1931 to 1935 was published in 1941 (reprint of whole, Koenigstein, 1979–80).

Two books deal in particular with botanical illustrations. Claus Nissen's *Die botanische Buchillustration. Ihre Geschichte und Bibliographie. Zweite Auflage. Durchgesehener und verbesserter Abdruck der Erstauflage ergänzt durch ein Supplement*, three volumes in one (Stuttgart, 1966). Volume 3, a supplement to the original edition (1951), was also published separately. The second work is Sacheverell Sitwell and Wilfred Blunt's *Great Flower Books, 1700–1900 ... The bibliography edited by Patrick M. Synge* (London, 1956). Blunt was also the co-author with W.T. Stearn of *The Art of Botanical Illustration*, London, 1950 (the 4th enlarged edn, 1967, was reprinted in 1971). There are two guides to old herbals, both of which contain considerable bibliographical information: Agnes Arber, *Herbals. Their Origin and Evolution. A chapter in the history of botany 1470–1870* (Cambridge, 1912; 2nd edn 1938; 3rd edn with an introduction and annotations by William T. Stearn, Cambridge 1986); and Alfred Schmid, *Ueber alte Kräuterbücher* (Bern and Leipzig, 1939).

N. Douglas Simpson has compiled *A Bibliographical Index of the British Flora, including floras, herbals, periodicals, societies* (privately printed, 1960). This is based largely on the compiler's library of some 5400 books on the British flora, and on his collection of periodicals.

A guide to the literature of agriculture is provided by J. Richard Blanchard and Harald Ostvold's *Literature of Agricultural Research* (Berkeley, 1958) in which entries are arranged under broad headings, and then subdivided into: bibliographies of bibliographies and general works; abstracting journals; bibliographies and indexes; encyclopaedias; dictionaries; handbooks; yearbooks; history and biography; geography; abbreviations; periodical lists; societies and organizations; tables. Although primarily devoted to American publications important foreign works are included and many of the references are annotated. Equally focusing on American agriculture is John T. Schlebecker, *Bibliography of Books, Pamphlets on the History of Agriculture in the United States 1607–1967* (Santa Barbara, CA, 1969) which lists 2000 publications by author.

A bibliography devoted to British agriculture was compiled by Walter Frank Perkins as *British and Irish Writers on Agriculture* (3rd edn, Lymington, 1939). This includes books on agricultural chemistry, botany, entomology, grasses, weeds, as well as lists of journals and newspapers, with a subject index to the entries numbering about 2000 and dating from about 1600 to 1900. Perkins's collection of agricultural books is housed at the University of Southampton, which has issued a *Catalogue of the Walter Frank Perkins Agricultural Library*

(Southampton, 1961). This contains a memoir of Perkins. George Edwin Fussell, a prolific writer on the history of agriculture,[24] compiled the aptly subtitled *Agricultural History in Great Britain and Western Europe before 1914: a discursive bibliography* (London, 1983).

Catalogues of botanical libraries, while not themselves bibliographies, are valuable guides to bibliographical research. Four examples connected with the history of botany and agriculture will be mentioned. *Catalogue of the Printed Books and Pamphlets in the Library of the Linnean Society of London* (London, 1925) is an alphabetical list by authors. The Royal Horticultural Society's *The Lindley Library: catalogue of books, pamphlets, manuscripts and drawings* (London, 1927) has been kept up to date by lists of additions in the Society's *Journal*. Mary S. Aslin and E.J. Russell compiled the catalogue of the collection at the Rothamsted Experimental Station, Harpenden, published in a second edition as *Library Catalogue of Printed Books and Pamphlets on Agriculture, published between 1471 and 1840* (Harpenden, 1940). Finally, the Forestry Commission's *Library Catalogue of Books, with lists of periodicals and Forestry Commission publications* (London, 1957) covers horticulture, botany and soil science, and is particularly good for details of conferences.

Periodically published guides to botanical literature include the *Botanischer Jahresbericht* (10 vols, Berlin, 1873–82) which was continued as *Just's botansicher Jahresbericht* (1883); *Botanischer Zentralblatt: referierendes Organ für die Gesamtgebeit der Botanik des In-und-Auslandes* (40 vols, Cassel, 1880–1919) of which a new series began in 1920. Work after this date is traceable through *Botanical Abstracts*.

Although not originally issued for sale, and printed in an edition limited to 750 copies, the catalogue of the Rachel McMasters Miller Hunt Botanical Library, Carnegie Institute of Technology, Pittsburgh, must be noticed because of the wealth of its contents. Compiled by Jane Quinby and entitled *Catalogue of Botanical Books in the Collection of Rachel McMasters Miller Hunt*, volume 1, published in 1958, covers printed books, 1477–1700. The second volume in two parts compiled by Allan Stevenson, 1961, covers 1701 to 1800; and 1801 to 1850. The volumes, which were reprinted commercially in New York, 1991, also contain valuable essays on the history of botany, and a survey of early printing as represented in this remarkable collection. The Hunt Botanical Library is virtually an international institute for bibliographical studies of botanical and horticultural literature. It intermittently published the *Hunt Facsimile Series; Hunt Monograph Series; Bibliographia Huntiana*, and *Huntia*, a yearbook begun in 1964 devoted to studies in botanical bibliography.

Technology

One of Wilhelm Engelmann's many bibliographies is *Bibliotheca mechanico-technologica, oder Verzeichniss der ... bis zu Anfang des Jahres 1834 in*

Deutschland und den angrenzenden Ländern erschienen Bücher über alle Theile der mechanischen und technischen Künste und Gewerbe, Fabriken, Manufacturen (2 parts, Leipzig, 1834–39; with a second much-expanded edition, also in 2 parts, Leipzig, 1844–50, reprinted Hildesheim, 1970). An interesting, but expensive, catalogue of a modern collection of books on mechanics is Verne Roberts and Ivy Trent, *Bibliotheca Mechanica* (New York, 1991). Roberts' personal collection runs to about 1200 items listed in alphabetical order; collations are given only for books published before 1800.

The best modern starting-point for research in history of technology is Eugene S. Ferguson, *Bibliography of the History of Technology* (Cambridge, Mass., 1968). This is a comprehensive guide to the primary and secondary literature, based on and expanding, *Technology & Culture's* 'Current bibliography in the history of technology' which has appeared annually since 1964. Two other guides in the Garland series are John Peter Oleson, *Bronze Age, Greek and Roman Technology. A select, annotated bibliography* (New York, 1986), which cites over 2000 entries; and David F. Channell, *The History of Engineering Science. An annotated bibliography* (New York, 1989), which lists 1494 books and papers on general bibliography, the interaction of science and technology, biography, institutions, mechanics, thermodynamics and fluid mechanics. A briefer, more deeply personal, bibliography of the history of technology by Arnold Pacey is to be found in the afore-mentioned *Information Sources* edited by Corsi and Weindling. Ian McNeil, *An Encyclopaedia of the History of Technology* (London and New York, 1990) has short bibliographies at the end of each section, but is pale in comparison to the historiographical sophistication demonstrated by the two later volumes in this series devoted to medicine and mathematics (see above).

There are two specialized bibliographies on civil engineering: A.W. Skempton, *British Civil Engineering 1640–1840. A bibliography of contemporary printed reports, plans and books* (London and New York, 1987) covers fen drainage, river and canal navigation, docks, harbours, bridges, roads, railways and water supply, as well as abstract reports on the strength of materials and hydraulics. It is arranged alphabetically according to authors or commissions (e.g. Forth & Clyde Canal). The other is Darwin H. Stapleton (with Roger L. Shumaker), *The History of Civil Engineering since 1600, an annotated bibliography* (New York, 1986) which has 1283 entries.

Dominick A. Pisano and Cathleen S. Lewis (eds), *Air and Space History. An annotated bibliography* (New York, 1988) is compiled by specialists at the National Air and Space Museum, Smithsonian Institution, and complements Paul Brockett's annual *Bibliography of Aeronautics* issued by the Smithsonian Museum between 1909 and 1937.

John E. Findling and Kimberly D. Pelle (eds), *Historical Dictionary of World's Fairs and Expositions, 1851–1988* (New York and London, 1990) provides both a basic description of each exposition and a bibliography of primary and secondary literature on each event. Many such fairs played key roles in a country's scientific and technological history.

George Sang Duncan, *Bibliography of Glass. (From the earliest records to 1940)* (Sheffield, 1960) contains nearly 16,000 references arranged alphabetically by author.

Finally, a bibliography of books, pamphlets, catalogues and articles on, or connected with, historical studies on scientific instruments are published regularly in the *Newsletter* of the Scientific Instrument Commission of the International Union of the History and Philosophy of Science. The first 13 of these bibliographies assembled by G.L'E. Turner and D.J. Bryden have been published as *A Classified Bibliography on the History of Scientific Instruments* (Oxford, 1997). Turner published an excellent bibliographic survey of the field as it existed in 1983 in Corsi and Weindling's *Information Sources.* A useful inventory of known surviving copies of instrument makers' trade catalogues has been compiled by R.G.W. Anderson, J. Burnett and B. Gee as *Handlist of Scientific Instrument-Makers' Trade Catalogues 1600–1914*, (Edinburgh: National Museums of Scotland, 1990).

Epilogue

'The good bibliographer must be like the good collector, tenacious and faithful; like him, he is sustained by his love of the collection, though he does not wish to secure physical possession of the objects; he is happy enough if he has been able to examine them, to describe them and register them to the Republic of Letters.'[25]

Notes

1. Thackray, A. and Merton, R.K. (1972), 'On discipline building. The paradoxes of George Sarton', *Isis*, 63, 473–95; Thackray, A. (1980), 'The pre-history of an academic discipline. The study of the history of science in the United States,' *Minerva*, 18, 448–73. Strelsky, K. (1957), 'Bibliography of the publications of George Sarton,' *Isis*, 48, 336–50.
2. Salié, Hans (1960), 'Poggendorff and *Poggendorff*', *Isis*, 57, 389–92.
3. See also Beretta, Marco (1993), *A History of Non-Printed Science. A select catalogue of the Waller collection*, Uppsala.
4. The JANET address is uk.ac.ucl.wihm and that of the Internet wihm.ucl.ac.uk.
5. Munby, A.N.L. (1968), *The History and Bibliography of Science in England: the first phase 1833–1845. To which is added a reprint of the Catalogue of scientific manuscripts in the possession of J. O. Halliwell, Esq.*, Berkeley, CA. See also Hornberger, T. (1949), 'Halliwell-Phillips and the history of science', *Huntingdon Library Quarterly*, 12, 391–99.
6. De Morgan's books are to be found in the University of London Library, Senate House.
7. In *Bullettino di Bibliografia e de storia della scienze matematiche e fisiche*, 1881–82.
8. Winder, Marianne (1966), 'A bibliography of German astrological works printed

between 1565 and 1600, with locations of those extant in London libraries', *Ann. Sci.*, 22 (1966), 191–220.

9. Forbes, E.J. (1973), 'The Crawford collection of books and manuscripts on the history of astronomy, mathematics, etc., at the Royal Observatory, Edinburgh', *British Journal History of Science*, 6 (1973), 459–61.
10. The essay is reproduced in Gingerich, O. (1992), *The Great Copernicus Chase and Other Adventures in the History of Astronomy*, Cambridge, England and Cambridge., Mass., pp. 69–81.
11. Also issued as a monograph by the Babson Institute Library, Babson Park, Mass., 1953.
12. Volume 2 (1961) covers the period from Leonardo to Boerhaave; volume 3 (1962) deals with the eighteenth century, but begins with French chemistry since 1600; volume 4 (1964) is concerned with the nineteenth century and a more limited coverage of early twentieth-century chemistry. Only the first part of volume 1 (1970), on the Greek philosophical basis of European chemistry, was published. Material on Arabic and European alchemy was too incomplete on Partington's death to warrant editing for publication.
13. Josten, C.H. (1960), 'Elias Ashmole, F.R.S. (1617–1692)', *Notes Rec.Roy.Soc.Lond.*, 15 (1960), 221–30. Also Josten, C.H. (ed.) (1966), *Elias Ashmole (1617–1692). His autobiographical and historical notes, his correspondence, and other contemporary sources relating to his life and work*, 5 volumes, 1966.
14. See also MacPhail, Ian (1967), 'The Mellon Collection of Alchemy and the Occult,' *Ambix* 14, 198–202.
15. See Sarton, G. (1948), 'John Ferguson (1837–1916)', *Isis*, 39, 60–61.
16. Richter, F. (1957), *75 Jahre Beilsteins Handbuch der Organischen Chemie*, Springer Verlag, Berlin.
17. School of Librarianship thesis, University of London; copy at University College, London.
18. Alwyne Wheeler, C. (1956), 'The *Zoophylacium* of Laurens Theodore Gronovius', *J. Soc. Bib. Nat. Hist.*, 3 (1956), 152–57.
19. Griffin, F.J., Davies Sherborn C., and Marshall, H.S., 'A catalogue of papers concerning the dates of publication of natural history books', *J. Soc. Bib. Nat. Hist.*, 1 (1936), 1–30; first supplement by Griffin, ibid., 2 (1943), 1–17; second supplement by W.T. Stearns and A.C. Townsend, ibid., 3 (1953), 5–12; third supplement by G.H. Goodwin, ibid., 3 (1957), 165–74; fourth supplement by Goodwin, Stearns and Townsend, ibid., 4 (1962), 1–19.
20. Travis Jenkins, James (1948), 'Bibliography of whaling', ibid., 2, 71–166.
21. Cleevely, R.J. (1974), 'A bibliography of the Sowerby family', *J. Bib. Nat. Hist.*, 6, 418–81.
22. Bridson, G.D.R. (1968), '*The Zoological Record* – a centenary appraisal', *J. Bib. Nat. Hist.*, 5, 23–34.
23. See Thompson, Lawrence S. (1962), 'Jens Christian Bay, bibliologist,' *Libri*, 12, 320–30.
24. University of Reading (1967), *G.E. Fussell: a bibliography of his writings on agricultural history*, Reading.
25. Sarton, George (1950), 'The Critical Bibliographies of Isis', *Isis*, 41, 291–98.

Chapter Ten

Scientific Books and their Owners: a survey to c. 1720

Giles Mandelbrote

Why make a scientific library?

> His very Bed-Chamber, was so extreamely crowded with Boxes, Glasses, Potts, Chymical & Mathematical Instruments; Bookes & Bundles of Papers; that there was but just roome for a few Chaires; so as his whole furniture was very Philosophical, without formality: There were yet other Roomes, and a small Library (and so you know had *Descartes*) as learning more from Men, Real Experiments, & his Laboratory (which was ample and well furnish'd), than from Books.[1]

John Evelyn's somewhat dismissive reference to the books belonging to Robert Boyle (1627–91), the most respected English scientist of his time, vividly evokes the crowded surroundings of a seventeenth-century personal library, and also presents us with some of the issues of historical context that apply more generally to scientific book collections in this period. Books jostle for space with laboratory glasses and mathematical instruments, in terms of physical arrangement but also of intellectual priority. As Evelyn points out, there were tensions between an experimental approach to natural philosophy and the pursuit of scientific knowledge through the acquisition of books. These tensions are plain enough in the writings of Bacon and Descartes themselves, in the Royal Society's motto 'Nullius in verba', and in the controversies between the Ancients and the Moderns.[2]

In the debates between the Royal Society and its critics, for instance, the library and the laboratory were represented as symbols of opposing traditions – the old argument from learned authority, proceeding by citation and synthesis of classical and Biblical texts, as against new, empirical methods of inquiry,

using measurement and observation. 'Those who have the best faculty of *Experimenting*,' wrote the Royal Society's historian, 'are commonly most averse from reading Books.'[3] A practising scientist in this period might therefore be expected to have been a collector of mathematical, astronomical or scientific instruments, of natural history specimens and other material for experiments, but not, perhaps, to have owned or used many books. In fact, however, this distinction is little more than a rhetorical device, invented to bolster the image of the man of science as discoverer of new and objective truths.

Another eyewitness description of Boyle's library, written soon after his death, gives a completely different impression of its size: 'yesterday I took Mr Ch. and Mr Holsworthy to visit Mr Boyles Library. we saw a very strong digestive that would Supple the hardest bone. a good Collection of Mineralls and oars and earths. I had before seen his Library containing 330 fol[ios]. 801. q[uar]tos 2440 Oct[avos]. and 12.[duodecimos] most of them well bound they may be had for 3 or 400 £ (tho' worth 1000) because they must not be sold by Auction.'[4] Here again it is striking that books are mentioned as only one of the collections contained in the library. Three and a half thousand volumes, however, constituted by no means 'a small library' for the time: Evelyn's own library, one of the largest personal collections made in England during the second half of the seventeenth century, contained nearly 5000 works.

Scientific books were not, for the most part, collected self-consciously to the same extent as curiosities, scientific specimens and other objects. There were good practical reasons, by contrast, for the growth of personal scientific libraries and the widening ownership of scientific books during the course of the seventeenth century. The historical context for the development of early modern science – and for intellectual activity of all kinds – remained one in which knowledge was packaged in book form. Few scientists of this period imagined natural philosophy to exist in an intellectual vacuum, or wished to conduct their own work without reference to the findings and experiments of others. Much could be achieved by elaborate networks of correspondence: in the 1640s, for instance, Samuel Hartlib proposed an office of address to facilitate communication of this sort as part of his scheme for the reform of knowledge, which also laid down rules for libraries; Théophraste Renaudot developed a Bureau d'Adresse in Paris under royal patronage. Similar motives lay behind the development of printed scientific periodicals, such as the *Journal des Sçavants* and the *Philosophical Transactions*, published from 1665 onwards, which disseminated news of the Royal Society's meetings and foreign correspondence. These initiatives did not displace more substantial printed books, however, as the most important vehicle for recording and communicating scientific theories and discoveries. The original statutes (1663) of the Royal Society, for example, recognized this in making provision both for a library and for the appointment of an official printer or bookseller.[5] Early scientific periodicals devoted much space to reviews and summaries of recent publications. Correspondence between scientists in this period is filled with

lively discussions about books, enquiries as to how they might be obtained and speculation as to when the next may be likely to appear.[6]

The most distinctive characteristic of the dissemination of science, by comparison with other forms of knowledge, was not the printed medium, but rather the problem of access to the latest scientific books. The absence of contemporary scientific texts from many university curricula, coupled with the traditional dependence of institutional libraries upon bequests from previous generations, meant that personal book collections were all the more essential for individuals with a serious interest in science, if they could afford them. Roman Catholic universities, such as those in Italy or at Paris or Louvain, either prohibited or severely restricted the teaching of the theories of Copernicus, Galileo and Descartes, although the books themselves were sometimes acquired for the purposes of refutation. In Oxford, despite the continuing domination of the curriculum by Aristotelianism, some college libraries had acquired the works of Descartes, Gassendi and other scientists by the later seventeenth century and had begun to purchase journals such as *Philosophical Transactions* and the *Journal des Sçavants*. Here as elsewhere, however, institutional changes appear to have lagged considerably behind the interests and enthusiasms of individuals.[7] In Cambridge, for example, it was not until 1715, with the donation of the library of John Moore (1646–1714), Bishop of Ely, that the University Library acquired copies of Newton's *Principia* (1687) and *Opticks* (1704), Hooke's *Micrographia* (1665) and several other important scientific works.[8]

Throughout the early modern period, moreover, scientific enquiry was generally regarded as contributing to an interlocking framework of knowledge, a picture of how the world fitted together, to which every educated person could aspire and whose ultimate purpose was to enhance human understanding of the glory of God. Natural philosophy was the handmaiden of theology. Contemporaries thought and wrote in terms of a continuum of disciplines; they would not have recognized the distinctions implicit in the modern term 'scientist'. This view owed much to the continued vitality of medieval traditions, despite the increasing specialization of mathematics and science by the end of the seventeenth century. Faith in a common core of knowledge, and curiosity about all its aspects, ensured that scientists' libraries contained books relating to a broad range of subjects and that scientific books quite naturally found their way to non-specialist readers. Robert Boyle's international reputation, for example, was due not only to his observations on natural philosophy, but also to his piety, his charitable activities, his enthusiasm for propagating translations of the Bible and his own devotional publications.[9] The lawyer and book collector John Selden – a scholar not usually associated with strong scientific interests – owned a substantial group of books on mathematics, optics and astronomy, including works by Copernicus, Galileo, Kepler, Descartes and Gassendi.[10]

This sense of confidence that wide-ranging knowledge was intellectually attainable was mirrored by confidence that it was possible to assemble a correspondingly encyclopaedic personal library. As Peter Laslett has observed, in his

edition of the library catalogue of the philosopher John Locke: 'Only in Europe and during the first two centuries after printing began ... could a man hope to build up for himself a collection of books so complete that nearly all his work as an author might be done with their aid alone.' Locke's library is one example of a large scholarly working collection, consisting of some 3600 separate titles. Subject classifications are, of course, highly subjective and provide only a very rough guide to an individual's interests and priorities. An analysis by subject of Locke's library suggests, however, that about a quarter of his books related to theology or Biblical scholarship; more than ten per cent were concerned with, respectively, medicine (which Locke had originally practised), law and politics, and classical literature; while geographical, philosophical and scientific works each accounted for about seven per cent of the total.

Among Locke's scientific books, the emphasis was on the works of his contemporaries, such as Huygens and Malpighi, rather than on older works. Pride of place belonged to works by Robert Boyle, with no fewer than 62 entries in the catalogue. Many of these would have been given to Locke by their author: some of the surviving volumes bear presentation inscriptions. As a Fellow of the Royal Society, Locke subscribed to a set of the *Philosophical Transactions*, which he took trouble to keep complete, as well as Sprat's *History*. Microscopy, a popular subject of virtuoso conversation, was present in the form of Hooke's *Micrographia* and four works by Jan Swammerdam. There was a good selection of the works of Francis Bacon, including the *Novum Organum*, *New Atlantis*, *Sylva Sylvarum*, and several editions of his *Essays*. In other areas, Locke's scientific holdings perhaps suggest a less determined interest: he owned a copy of the works of Galileo, but little of the related literature, and one work by Paracelsus. Locke, of course, can hardly be considered a typical owner of such books: as a young man, he had conducted experiments with Robert Boyle; he was well connected with some of the leading scientists of his day and had an extensive correspondence with European men of letters, much of it relating to the acquisition of books. Yet his library is like others of the time in that, while containing an impressive array of important works relating to natural philosophy, it cannot be neatly classified either as a scientist's library or as a scientific collection.[11]

Curiosity about natural philosophy also had a social and cultural dimension, distinctive to the virtuoso tradition of the late sixteenth and seventeenth centuries, which found expression in particular in the ownership of material objects – natural curiosities and scientific instruments, as well as books.[12] Scientific books and periodicals thus found their way into the libraries of the interested amateurs who formed the wider scientific community and who had the means and the leisure to pursue their interests in a serious manner. The acquisition of books was one of the ways by which members of this community defined themselves: as the scientific virtuoso became more self-conscious, so his library grew. Without this market it is likely that many of the most important (and expensive) scientific publications of the period would not have been commercially viable.

Books served as a focus for the social relationships that existed within this community: gifts and exchanges of books were naturally an important part of the reciprocal flow of ideas and information; fulsome dedications and special presentation copies might be offered as a recognition of patronage, in the hope of subsidies for publication, or by authors seeking perquisites and promotion.[13]

Ownership of scientific books was not, of course, limited to practitioners of natural philosophy, university men, wealthy amateurs, or any other particular category. The practical applications of science, for example, brought it into the field of interest of a much wider range of individuals, who put these to use in earning their living: merchants who needed to understand the principles of accounting; seamen whose navigation depended on astronomy; military men interested in ballistics or fortifications; architects, engineers and ship-builders; surveyors, gardeners and farmers; physicians, surgeons and apothecaries; instrument-makers, musicians, and many others with specialized skills. Any of these might wish to know more about the scientific background and might also need to own examples of a genre that became increasingly common in the course of the seventeenth century: treatises and handbooks which popularized scientific theories and used them as the basis for practical advice.[14]

During the sixteenth and seventeenth centuries, personal libraries containing works which we would now recognize as important in the historical development of science were formed for a variety of reasons and in many diverse circumstances. None of these libraries, arguably, should be considered a *collection* in the modern sense of scientific book collecting. A.N.L. Munby, the great bibliographer of British book sale catalogues, took the view, however, that some pioneer collectors might still be identified:

> whereas we already have reasonably full accounts of collectors of *incunabula*, early English literature, illuminated manuscripts, autographs and music, no similar attempt has been made systematically to survey on a substantial scale those who collected early scientific books. Such a survey ... would take one back into the seventeenth century, where it would be necessary to try to disentangle the antiquarian from the scientific interests of such men as Elias Ashmole. Some yardstick would have to be evolved by which one could differentiate between men who had a practical and an historical interest in science. One such test which occurred to me ... would be to examine the sale catalogues of the libraries of the eighteenth-century collectors and to look up the Newton entries. Most of them would contain the third or 'best' edition of Newton's *Principia*, 1726, a standard book without which no gentleman's library was complete. Some collectors, however, thought it desirable to acquire, in addition to the standard text, the first edition of 1687.[15]

Munby's suggestion for a 'yardstick' has not yet been put to the test, but his comments draw attention to some problems with the sources for the study of scientific libraries, not least concerning the methods and motives of book owners. To infer specific interests in the *history* of science on the grounds of the ownership of more than one edition of a book seems to be going too far. Without additional evidence, it is rarely clear from a library list or sale cata-

logue whether the presence of old editions (for example) results from accidents of acquisition, inertia or inheritance, or from design – unless the pattern is repeated several times. In broad terms, rare, old and historically significant printed books, rather than those distinguished by their textual importance or physical appearance, do not seem to have begun to attract collectors in northern Europe until the second half of the seventeenth century.[16] The collecting of landmark publications in the history of science was essentially a development of the nineteenth century. Munby himself has documented elsewhere the changing fortunes of the first edition of Newton's *Principia* in the antiquarian book market: 'Published at ten or twelve shillings, the price rose rapidly when the book went out of print, and Sir William Browne counted himself fortunate when he had to pay only two guineas for a copy in 1707. This scarcity value did not, of course, survive the publication of the second and third editions of 1713 and 1726 ... For a century and a half after 1750 the first edition was neglected by collectors.'[17]

One might nevertheless be able to draw up a list of some particular books whose combined presence in a library in the seventeenth century would be indicative not only of a serious interest in mathematical and scientific subjects, but also of an engagement with the contemporary debates and discoveries which were changing the intellectual landscape. Works on astronomy, by Copernicus, Kepler, Galileo or Tycho Brahe, would be an important category, and so might the medical discoveries of Harvey, or Gilbert's work on magnetism. Someone interested in a comprehensive interpretation of the natural world could not ignore the works of Descartes and Bacon, whose ideas were further diffused through a wide circle of followers. For the development of mathematics in England, Henry Billingsley's translation of Euclid's *Elements*, with John Dee's famous preface setting out the various mathematical and methodical arts, would be another important text.

In addition to bibliographies such as Gesner's *Bibliotheca Universalis* (Zurich, 1545), some specific guidance about what to put in a library was already available in print. Most interesting perhaps was the *Advis pour Dresser une Bibliothèque* (Paris, 1627; 2nd edn 1644), written by Gabriel Naudé (1600–53). Naudé was the librarian to Cardinal Mazarin and had scientific interests himself: among his other works was a rationalist defence of the reputation of figures such as Roger Bacon, Pythagoras and Cornelius Agrippa, who were accused of magic. His *Advis* is also of interest because it was translated into English by John Evelyn as *Instructions concerning Erecting of a Library* (London, 1661) and in this form reached the early Fellows of the Royal Society, among others. Naudé's recommendations started with the principal authors, ancient and modern, in every field of learning, and the authors of specialist works within these fields. He mentioned Ptolemy, Firmicus, Haly, Cardano, Stoeffler and others for astrology; Alhazen, Bacon and Aguillon for optics; Diophantus, Boethius, Jordanus, Tartaglia, Siliceo, Luca di Borgo, and Villefranche for arithmetic. Commenting on specialist studies, he singled out the work of Vesalius on

anatomy, Mattioli on plants, Gesner and Aldrovandi on animals, Rondelet and Salviani on fishes, Vicomercatus' commentary on Aristotle on meteors, and Gilbert on the lodestone. Naudé considered that the most important controversial works should also be recommended, together with works that have modified accepted knowledge: in the latter category, he cited the transformation of astronomy by Copernicus, Kepler and Galileo.[18]

Early modern scientists attempted to understand their own experience and bring order to the world by developing a systematic method and devising classification schemes for knowledge. When it came to using books and organizing libraries, they applied the same prescription of hierarchy and taxonomy.[19] Their letters and commonplace books are full of bibliographical notes, lists of desiderata and titles drawn from other books, bibliographies and catalogues, books seen in shops or in the libraries of friends – extracted, digested, epitomized, subject-indexed, cross-referenced, and rearranged (on paper) on idealized shelves.[20]

The tall trees of intellectual history, which we can see with hindsight, may yet prove to be less substantial than the low thickets of so many libraries of this period. Any canon of scientific works must be viewed in its intellectual context – in terms of contemporary opinion and the process by which ideas were diffused and accepted over time. The presence (or absence) of major scientific works in an individual's library should likewise be interpreted in the context of the library as a whole and of the opportunities for making such acquisitions – travel, inheritance, wealth, friendships, chance. Rather than the famous books of science, it may often be the strength in groups of printed books, perhaps obscure or not obviously scientific, and the related manuscript material that show how a library fits together intellectually and reveal most accurately a particular owner's personality, interests and priorities.

Sources for the ownership history of scientific books

Leaving aside the issue of motivation, various forms of evidence – each with its own limitations – shed light on book ownership in the early modern period. Catalogues of the contents of some great libraries, for instance, were drawn up from time to time for housekeeping purposes. Much more broadly based as a source are inventories of the personal possessions of individuals, usually drawn up after death for the purposes of probate. Inventories of personal estates, sometimes with valuations, have survived in considerable numbers from this period, for many levels of society and in many western European countries. The main problems with this evidence are two-fold: post-mortem inventories relate only to a particular (and very untypical) moment and give little sense of the changes over time in a collection of books; the age of the deceased owner is an important factor, as is the possibility that some items may have been sold much earlier, given away or held back by executors. Secondly, books were

frequently considered too complex and insufficiently valuable objects to merit detailed or careful description: it may prove impossible to identify particular editions, or even particular texts, or to be sure of distinguishing manuscripts from printed books. In the course of the seventeenth century, as printed books became more numerous and came to be regarded as common household possessions, inventories ceased even to try to list them individually by title. Practice depended on the individuals responsible for drawing them up, but a general change is certainly noticeable in English inventories by about 1700. Inventories, nevertheless, when sampled over a reasonably long period and in sufficiently large numbers, permit us to observe the gradual diffusion of scientific and mathematical books across much of Europe, following on the whole a similar path, although varying considerably in chronology from one country to another.

Proximity to North Africa had ensured that during the Middle Ages Arab mathematical, scientific and astronomical manuscripts continued to have some circulation in Spain and Italy. Interest in these subjects in Italy, in particular, was stimulated by the rediscovery of Greek mathematics in the late fourteenth century, and also by mercantile expansion in the Mediterranean and the skills necessary to sustain it. This practical interest was given further impetus by the spread of printing a hundred years later. In Florence in the fourteenth and fifteenth centuries, for instance, teachers of commercial arithmetic owned celebrated collections of works on arithmetic, geometry, astrology, music, perspective and architecture.[21] A study based on fifteenth and sixteenth-century inventories of small Florentine libraries, mainly the property of professionals and merchants, found that books on astronomy and astrology became popular from about 1470, at the same time that commercial manuals were being recorded in larger numbers. The sixteenth century saw a gradual change and secularization in the overall composition of these libraries: works of devotion and theology came to play a less important part, in numerical terms, while there was an increase in the proportion of technical and professional books, on subjects such as arithmetic, astronomy, navigation, agriculture, natural history and medicine.[22]

These small-scale professional libraries form an interesting counterpoint to the great collections of manuscripts being assembled during the early Renaissance in Florence, Rome and Venice. From the end of the fourteenth century, Greek codices on mathematical subjects, particularly astronomy and geometry, were enthusiastically collected by Florentine scholars, who brought them back from Byzantium and hunted for them in Italian monastic libraries. Scholars worked on new translations of Ptolemy and Archimedes and rumours abounded of the discovery of manuscripts of lost works. In these humanist circles, an interest in mathematics combined easily with a broader curiosity about classical culture, literature, philology, architecture and history. The best-known mathematician in Florence, Paolo dal Pozzo Toscanelli (1397–1482), who formed a substantial collection, was the friend of the architects Alberti and Brunelleschi, as well as the mathematical correspondent of Nicholas of Cusa and of Johann

Müller of Königsberg, usually known as Regiomontanus. The greatest libraries in Florence, however, were formed by the ruling Medici family, building on the work of the first generation of scholar-collectors: the public library, which opened in 1444 in the monastery of San Marco, incorporated the collections of Niccolò Niccoli (c. 1364–1437) and Ser Filippo di Ser Ugolino Pieruzzi (1388–1454), who was noted for his mathematical interests. The private household library of the Medici expanded rapidly in the second half of the fifteenth century; the acquisitions made by Janus Lascaris (1445–1535) and Angelo Poliziano (1454–94), scholars acting as agents for Lorenzo de' Medici, included numerous Greek mathematical manuscripts. Many of these are recorded in surviving contemporary inventories of the collection and are now in the Biblioteca Laurenziana in Florence.[23]

Institutional inventories also make it possible to trace the rapid growth of the Vatican Library under Pope Nicholas V (1447–55) and Pope Sixtus IV (1471–84). Significant acquisitions, following the fall of Constantinople in 1453, included Greek manuscripts containing mathematical texts by Apollonius, Diophantus and Euclid; manuscripts were also copied on a large scale and new translations were commissioned, most notably of Archimedes, the *Almagest* of Ptolemy, and the zoological and botanical writings of Aristotle and Theophrastus. Another library, that of Cardinal Bessarion (1403–72), surpassed even the Vatican, for a time, in its collection of Greek manuscripts. The German astronomer Regiomontanus was a friend of Bessarion and, like a number of other scholars, borrowed codices from the library, which contained almost every classical mathematical text of importance. An inventory of Bessarion's books in 1468 listed 43 Greek and 11 Latin manuscripts on mathematical or astronomical subjects; most of these are now in the Biblioteca Marciana in Venice. Venice, as the main port linking Italy to the eastern Mediterranean, was a centre for Greek studies and the home to many notable libraries, including that of the humanist Giorgio Valla (1447–1500), who prepared translations of Archimedes and Euclid. Valla's collection of mathematical manuscripts is known partly by a list compiled by Lascaris, who visited his house on behalf of the Medici, and also through the texts published by Valla himself in his encyclopaedic *De Rebus Expetendis*. Collectors such as these laid the foundations for the study of mathematics and astronomy in the sixteenth century.[24]

Across the rest of Europe, from the courts of Prague and Vienna to Spain, manuscripts of scientific texts found their way into royal and aristocratic collections, as scholars encouraged their patrons to form libraries relating to the rediscovered culture and science of the classical world.[25] One of the most important Spanish collectors, to give one example, was the wealthy and well-travelled diplomat Diego Hurtado de Mendoza (1503–75), who while ambassador to Venice took lessons in mathematics from Niccolò Tartaglia and prepared a Spanish translation of the Aristotelian *Mechanica*. His 400 Arabic, 200 Latin and 300 Greek manuscripts were bequeathed to Philip II and are now in the Escorial.[26]

Manuscript collections made by scientific practitioners themselves were perhaps more liable to dispersal and have often proved difficult to reconstruct. The library of Regiomontanus (1436–76) passed after his death into the possession of the town council of Nuremberg. In 1478, King Matthias Corvinus (1458–90) of Hungary sent an agent there to buy some of Regiomontanus' books and instruments. Over the following decades there were disputes over the estate and the library was depleted by theft. In 1522, an inventory recorded 215 books, of which 11 were printed; in the same year, however, it is known that some books were sold to Albrecht Dürer, including a copy of Euclid's *Elements* with Regiomontanus' annotations. Other books were acquired by Dürer's friend, the Nuremberg scholar Willibald Pirkheimer (1470–1530). Another document drawn up in 1563, in connection with a lawsuit, listed 148 items, of which 30 were printed books, some dating from after Regiomontanus' death. Thirty-four manuscripts now remain in the city library at Nuremberg.[27]

Inventories also provide evidence of some German mathematical libraries of the sixteenth century. Johann Scheubel (1494–1570), professor of mathematics at Tübingen, bequeathed his books and mathematical instruments to his university. A list of these records some 100 printed books and seven manuscripts, mostly relating to arithmetic, geometry and astronomy. Among these were texts of Euclid, Archimedes and Proclus, and also works by more recent German and central European scholars, such as Copernicus, Stifel, Johann Werner, Peter Apian and Christoph Rudolph. Another university professor, Caspar Peucer of Wittenberg (1525–1602), the son-in-law of Melancthon, owned a larger mathematical library, according to an inventory probably compiled in the 1580s. Peucer's books amounted to nearly 1500 volumes, half of them concerned with medicine and philosophy; particularly well represented were the works of German astronomers, including Peurbach, Regiomontanus and Lichtenberger, as well as Copernicus, Cyprian von Leowitz, Sebastian Münster and Erasmus Reinhold. Peucer's library appears to reflect a strong interest in contemporary German scholarship, relatively little influenced by the classical tradition; personal collections such as these, however, should also be considered in the broader context of the books available in contemporary institutional libraries.[28] Evidence about the wider ownership by individuals of scientific and technical printed books in sixteenth-century Germany is much more modest. Probate inventories of German artisan households do, however, suggest the growth of a new readership, as a consequence of the increasing availability of books and of reforms in vernacular education. Prominent among the new book-owners were barber-surgeons and apothecaries, whose books often reflected their practical occupational need for information about elementary chemistry or anatomy.[29]

The major scientific works of the sixteenth and seventeenth centuries, by contrast, were relatively expensive books, which remained well beyond the reach of artisans. The Frenchmen who bought the works of their contemporaries Mersenne, Gassendi and Descartes, for example, were usually wealthy professionals: lawyers, office-holders and physicians. The account-books of the

firm of Nicolas, booksellers in Grenoble from the 1640s to the 1660s, document the sale of works by Descartes, Gassendi, Bacon and Harvey to dignitaries at the head of the local governmental, fiscal and legal system. Parisian inventories provide some evidence that physicians in particular were interested in adding works of astronomy, cosmography and mathematics to their libraries, and that some of these libraries represented a serious attempt to bring together works of traditional learning and of modern science: copies of the *De Revolutionibus* (1543) of Copernicus, for instance, are recorded in the possession of three physicians: Lemaignan (1555), Lusson (1600), and Marescot (1605).[30] The inventory of the chemist Guy de La Brosse (d. 1641), who founded the botanical garden in Paris, documents a large and important collection of books on mathematics, astronomy, chemistry, alchemy and natural history, including works by Copernicus, Regiomontanus, Galileo, Kepler, Brahe and Gilbert, Paracelsus, Mizauld, Gesner and Aldrovandi.[31] Libraries such as these were exceptional, however; the inventories of the Parisian urban élite of the later seventeenth century suggest that, on the whole, their taste in scientific books inclined more towards the entertaining and the useful than towards serious scientific enquiry.[32] In the course of the century, scientific works – especially those with overtones of moral philosophy and erudite culture, or those relating to practical applications of science – became more fashionable throughout France, with the growth of a community of 'amateurs'. One example is the collection of the provincial magistrate and official Florimond de Beaune of Blois (1601–52), who was also the author of some treatises on solid geometry. Florimond de Beaune's inventory lists only 268 books, but more than half of these were concerned with science, including the entire works (to 1652) of Kepler, Galileo and Descartes, the most important scientific works of Mersenne and Gassendi, together with a comprehensive collection of mathematics.[33]

In England, possibly the most interesting inventory evidence relating to book ownership in this period comes from the two long series of probate inventories drawn up by the Chancellor's Courts of the universities of Cambridge and Oxford.[34] These inventories list the possessions not only of university students, but also of graduates, tutors, fellows and 'privileged persons' such as booksellers who died within the jurisdiction of the two universities. A survey of this evidence suggests relatively wide ownership of the most elementary mathematical textbooks: more than half the inventories recorded one or two copies of arithmetical and geometrical works by authors such as Gemma Frisius, Euclid, Ramus, Robert Recorde or Peter Ryff. Also noted with some frequency were cosmographical and astronomical manuals and, more traditionally, the scientific writings of Plato and Aristotle. A similar pattern of student book-ownership is apparent from the account books of Joseph Mede, a Fellow of Christ's College, Cambridge, between 1613 and 1638. Following what was probably common practice at the time, Mede ran a private secondhand book market for his pupils: works such as Keckermann's *Mathematica* and Blundeville's *Exercises* were among the textbooks recycled in this way. Much more occasionally, the ac-

counts record purchases such as Alsted's *Encyclopedia* (1620), Münster's *Cosmographia* (1572) and Ortelius' *Theatrum Orbis Terrarum* (1606).[35]

The inventories of the stock of two Cambridge booksellers Nicholas Pilgrim (1546) and John Denys (1578) give some impression of the modest range of scientific and mathematical works available there. Pilgrim's stock of some 382 items, in more than 700 volumes, included multiple copies of the *Arithmetica* of Gemma Frisius (three) and of the *De Sphaera* of Proclus (seven). Thirty years later, Denys appears to have offered a better selection, particularly of books on astronomy and practical subjects, including several works by Antoine Mizauld, such as his *Planetologia* and *Hortorum Secreta*, Offusius' *De Divina Astrorum*, John Holywood's *De Sphaera*, as well as Digges's *Pantometria* and Münster's *Cosmographia*.

For the most important – and more expensive – works of science, however, it is necessary to look to the inventories of established university men, who would have been more likely to acquire such books from the specialist importers of the London book trade, directly from other scholars, or through agents on the continent, than in the shops of the university towns.[36] Of the collections recorded in Cambridge inventories, the library of Andrew Perne towers above the rest. By the time of his death in 1589, Perne, who was Master of Peterhouse from 1554 and five times Vice-Chancellor, had amassed almost 3000 titles – this when a scholar's inventory might usually list perhaps 100 and the university library itself owned only about 500 printed books. Perne's interests in mathematics, astronomy, architecture, geography, natural history and other sciences were attested not only by a remarkable collection of instruments and maps, but also by copies of Copernicus' *De Revolutionibus* (1543), Dürer's *De Symmetria Partium* (1532), Agricola's *De Re Metallica* (1561), several astronomical works by Apian, Münster's *Cosmographia*, atlases and geographical works by Mercator, Ortelius and Christopher Saxton, and botanical and zoological works by both English (Thomas Hill and William Turner) and continental authors (Leonhard Fuchs, Gesner, Rondelet). Many of these books were bequeathed to Peterhouse, where they remain. The finest scientific library in Tudor Cambridge seems to have owed its existence purely to intellectual curiosity: Perne's career was that of a university politician and his only publication was a translation of Ecclesiastes and the Song of Solomon for the Bishops' Bible (1568).[37]

Among Perne's Cambridge contemporaries, two other scholars, John Hatcher and Thomas Lorkyn, both wealthy medical men, assembled notable, though much smaller, libraries, each of about 600 volumes. A number of the books listed in Hatcher's inventory (1587) were bequeathed to Lorkyn and reappeared in his inventory (1591). Among Lorkyn's medical books were numerous works by Paracelsus, as well as Vesalius' *De Humana Corporis Fabrica* (1543); the astronomical, mathematical and scientific authors included Mizauld, Digges, Stadius, Finé, Gemma Frisius, Euclid, Peucer, Fuchs and Gesner.[38]

Probate inventories of Oxford scholars also note some significant collections of scientific books. Thomas Pope, for instance, who died in 1578, only two

years after gaining his MA from St Mary's Hall, owned arithmetical works by Gemma Frisius, Record and Ramus, and works on astronomy by Dariot and Stoeffler, as well as a globe and some mathematical instruments. The library of Thomas Tatham, a Fellow of Merton College who died in 1586, contained treatises on arithmetic by Peltarius and Tunstall, and several works on medicine, astronomy, cosmography, astrology and magic. Another Fellow of Merton, Robert Barnes, bequeathed to his college in 1599 a collection of books which included works by Ptolemy, Euclid, Stoeffler, Regiomontanus and Copernicus. Supplementing such evidence is the benefactors' register of the Bodleian Library, which in 1600, for instance, listed the donation by William Gent of Gloucester Hall of some 400 books, most of them mathematical, astronomical or medical, and apparently from his own library. Gent's donation included works by Archimedes, Regiomontanus, Clavius, Commandino, Dürer, Finé and Copernicus, as well as Vesalius, Paracelsus, Fuchs and Gesner.

Comparable with Perne's library in Cambridge, though less fully studied, was the impressive collection of some 2500 volumes owned by John Rainolds, who was President of Corpus Christi College, Oxford, from 1598 until his death in 1607. Rainolds was one of the spokesmen for the Puritan party at the Hampton Court conference and shared in the translation of the Authorized Version of the Bible; his scholarly interests were wide-ranging and his chief expenditure seems to have been on books. His near-contemporary Joseph Hall, Bishop of Norwich, wrote of him that 'he alone was a well-furnished library ... the memory, the reading of that man were near to a miracle.' Rainolds's library catalogue records a large group of occult texts, by authors such as Plotinus, Ficino, Reuchlin, H.C. Agrippa and della Porta. In addition to these, he owned works on mathematics, astronomy, navigation, medicine, natural history and other sciences by Euclid, Archimedes, Gemma Frisius, Ramus, Apian, Mercator, Ortelius, Vitruvius, Aldrovandi, Fuchs, Gesner and Paracelsus, among others, coming right up to date with Francis Bacon's *Advancement of Learning* (1605).[39]

Manuscript lists and catalogues of libraries constitute another important source of evidence about book ownership over this period. Catalogues were usually compiled either by an owner of books as a finding-aid for his collection, or for an institution as a record of a donation or bequest, so the information provided may often be more precise than that given in an inventory. Catalogues of personal collections at this date varied greatly, however: some were extremely elaborate, including systems of alphabetical indexing, subject classification and cross-referencing; others were no more than rudimentary shelf-lists or registers of acquisitions. A common problem with this type of document is that crucial information such as the name of the owner of the books, or the date at which the list was drawn up, may often be omitted; it may also be difficult to distinguish lists of books owned from lists of desiderata or from bibliographical reference lists. There are a number of anonymous seventeenth-century book-lists, for instance, including items of scientific interest, among the manuscript collections of Sir Hans Sloane, now in the British Library.[40]

A survey of the ownership of books on agriculture in England between 1500 and 1650, based on a combination of inventories and contemporary catalogues, provides further evidence of the way in which scientific interests might overlap with practical obligations and be combined with the educational traditions of classical culture. The libraries of the great English landowners contained continental editions of the ancient texts of natural history and agriculture, such as Pliny's *Historia Naturalis*, alongside more recent continental works in the vernacular or in English translation – particular favourites were the *Maison Rustique* of Charles Estienne and Jean Liebault, translated by Richard Surflet, and Conrad Heresbach's work on husbandry, translated by Barnaby Googe and published under various titles. The library formed by William Cecil, Lord Burghley, contained works by Pliny, Aristotle and Gesner, Columella's *De Rerum Rusticarum* and Xenophon's *Oeconomicon*, as well as treatises on viticulture and silkworms. There was a large group of books relating to horses and their diseases, mostly in Italian. The collection of Sir Edward Coke, Lord Chief Justice under Elizabeth I, shows a similar emphasis on classical and continental agricultural science, although Coke also owned Thomas Tusser's *Five Hundred Points of Good Husbandry*. Ownership of agricultural books at a lower social level – among estate stewards, for example – has yet to be fully investigated and was of course subject to the constraints of price and literacy. It seems likely, however, that those somewhat closer to the ground provided the main market for the English-language adaptations, epitomes and practical manuals, the works of Tusser and Gervase Markham, and for the herbals of John Gerard, William Turner and their contemporaries.[41]

A number of the library catalogues of English book collectors of the seventeenth century have now been published and these illustrate, among other themes, the ownership of scientific books in the provinces, away from the political and educational centres of London, Oxford and Cambridge. Sir Thomas Knyvett of Ashwellthorpe (c. 1539–1618), for example, a member of the Norfolk country gentry, owned one of the largest recorded libraries of his time, containing more than 1400 printed books. Listed in his catalogue, drawn up in 1618, was a notable group of sixteenth-century Italian books on geometry, ballistics and military science, and an extensive collection of books on astronomy, including Copernicus' *De revolutionibus*, Bassantin's *Astronomique Discours* (Lyon, 1557) and works by Ptolemy, Holyrood, Giordano Bruno, Thomas Digges and Gemma Frisius. The seriousness of his mathematical interests are suggested by the presence of two editions of Euclid (Paris 1566 and Strasbourg 1564), as well as the English translation of 1570, and two editions of Digges's *Pantometria* (1571 and the enlarged edition of 1591). There are books about navigation and perspective, together with herbals and other works on natural history by Fuchs, Camerarius, Dodoens, and Gesner. The information provided by Knyvett's catalogue is supplemented by the survival of many of his books, which are now preserved in the Cambridge University Library.[42]

Another interesting catalogue of a provincial library belonged to a book collector in a very different mould, Samuel Jeake the elder (1623–90). Largely self-educated, Jeake served as town clerk of Rye, in East Sussex, during the 1650s and was active as a local nonconformist after the Restoration, apparently supporting himself in part by teaching arithmetic. A posthumous publication, *Logistekologia* (1696), testifies to the seriousness of Jeake's mathematical interests and also, in its preface, to his serious purpose as a collector of books:

> He that is sensible of the charge of buying, and trouble of turning over many Books to learn some one thing, will I doubt not excuse my further plea herein, and plead for me; especially if he knew that I speak not without Experience, of no little time and trouble to glean so many Fields for one Grist, having pickt up the knowledge of *Integers, Fractions, Figurals, Cossicks*, and *Surdes* principally from *Record, Decimals* from *Johnson, Astronomicals* from *Blundevile, Logarithmes* from *Briggs, Species* and *Æquations* from *Oughtred*, with a conference of many others.

Jeake's library catalogue of some 2100 items records in detail a range of mathematical works, from textbooks to more sophisticated treatises. Among these are Robert Recorde's *Whetstone of Wit* and *Ground of Arts*, Leonard Digges's *Pantometria* and *Stratioticos*, various works by William Oughtred, and Henry Billingsley's edition of Euclid, with its preface by John Dee. There is a notable group of works on applied mathematics, navigation and surveying, by authors such as Henry Briggs, Edmund Gunter, William Leybourne, Richard Norwood and John Tapp. The books on astronomy and astrology included works by Andreas Argol, Cyprian von Leowitz, J.A. Magini and Regiomontanus, as well as more recent works by Vincent Wing and Thomas Street. Jeake's interests also extended into alchemy and magic, with works such as Elias Ashmole's *Theatrum Chemicum Britannicum*, Cornelius Agrippa's *Occult Philosophy* and various treatises by Paracelsus and his circle. On natural history and agricultural improvement, Jeake owned Topsell's *History of Four-footed Beasts*, John Parkinson's *Paradisi in Sole*, and works by John Johnston, Walter Blithe, Thomas Tusser and Samuel Hartlib. More recent developments in natural philosophy were barely represented, however; Jeake owned a copy of Thomas Sprat's *History of the Royal Society*, but few other works by its members. An interesting feature of Jeake's collection is that many items appear to have been acquired secondhand and relatively cheaply, possibly at informal auctions or other dispersals of local libraries.[43]

The catalogues of auction sales of personal libraries, which in printed form first appeared in England in 1676, have long been recognized as an important source of information about libraries in this later period.[44] Their evidence has to be treated with some caution, however, owing to the trade's practice of intruding extraneous books, unannounced, into catalogues that purported to describe the collections of named individuals. The bookseller Robert Clavell – though not, perhaps, the most impartial observer – complained as early as 1681 about 'the imposing of old Rubbish out of Shops, and bad Editions of Books under pretence of eminent Mens Libraries'.[45]

The first English book auctioneer to adopt printed catalogues was William Cooper, who also specialised in books on chemistry and alchemy. Auctions may have been considered a particularly appropriate way of selling libraries of scientific interest, perhaps to encourage a spirit of competition among the virtuosi.[46] Notable early auctions of scientific libraries included those of the chemical collections of Dr Nathan Paget (sold 1681) and Thomas Britton (1694 and 1715), the mathematical books of Sir Jonas Moore (1684) and Sir Charles Scarburgh (1695), some astrological and astronomical books of Elias Ashmole (1694: most were bequeathed to the University of Oxford), the astronomical library of Edward Bernard (1697: the more important books were again bequeathed to Oxford), John Ray's collections of natural history and botanical books (1708) and the geological, mineralogical and botanical library of John Woodward (1728).[47]

Another difficulty that sometimes occurs in using sale catalogues is that libraries may be quite openly combined: *A Catalogue of a Choice and Valuable Collection of Books: being the Libraries of a late eminent Serjeant at Law, and of Dr Edmund Halley, Late Astronomer Royal* [1742], for instance, makes no separation between the two collections. One can be reasonably certain, of course, that the astronomical works were mainly Halley's: they form an impressive group, including the second edition of Copernicus (1566), an almost complete collection of the works of Hevelius, and others by Kepler, Newton, Tycho Brahe and David Gregory. Strangely, perhaps, the catalogue does not contain the first edition of Newton's *Principia*, which was published at Halley's expense. It is probable too that Halley owned most of the books on navigation and geography, as well as the unusually fine group of atlases, by Blaeu, Mercator, Ortelius and others, that are listed here. But the catalogue also contains numerous books on dancing, for example, and one is left to wonder whether these are more likely to have been the property of the eminent lawyer or the Astronomer Royal.[48]

A completely different line of enquiry into the ownership of scientific books stems from the possibility of identifying the provenance of a surviving volume or groups of volumes. The Bolognese naturalist Ulisse Aldrovandi (1522–1605), for instance, who founded the botanical garden there, bequeathed to his native city an important collection, including nearly 4000 books and manuscripts. The library was remarkable for its strengths not only in the field of natural history, especially ornithology, but also in medicine, alchemy, mathematics and geography. Losses suffered during the Napoleonic wars and other vicissitudes unfortunately compounded the confusion caused by the integration of Aldrovandi's books with other collections, in accordance with an eighteenth-century subject classification. Although various contemporary catalogues and indexes of Aldrovandi's library have been preserved, even some of these were amended to include details of later accretions. In recent years it has proved possible, however, to distinguish almost half the books from the original bequest, on the evidence of distinctive shelfmarks, bindings, ownership inscriptions ('Ulissis Aldrovandi et amicorum'), underlinings and marginal marks.[49]

At the death of Robert Burton (1577–1640), the author of *The Anatomy of Melancholy*, most of his books were divided between the Bodleian Library and the library of Christ Church, Oxford. Although Burton's books were also mixed up with others, his signature and marks of ownership, together with the evidence of the Bodleian benefactors' register and other lists, have enabled some 1500 items to be identified. These testify to the wide range of Burton's interests, and include works on medicine, astronomy, astrology and mathematics, and authors such as Tycho Brahe, Copernicus, Galileo, Gassendi and Kepler.[50]

Another library that has been identified largely by inference from surviving volumes and their annotations belonged to John Harrison (d. 1642), who was Head Master of Eton during Robert Boyle's time there and, by Boyle's own account, created in him 'a passion to acquire knowledge'. Harrison bequeathed to Eton a very impressive collection of scientific, mathematical and astronomical works. His library has been described as that of a well-informed amateur, who (as Naudé advised) collected the established works of the previous generation, including Copernicus, William Gilbert and John Napier, together with books that popularised their theories – such as works by Philip Lansberg, in the case of Copernicus – and books of controversy, such as the writings of Scheiner and Inchofer against Galileo, as well as Campanella's *Apologia*.[51]

Only in a few cases have seventeenth-century personal libraries reflecting serious scientific interests been preserved intact. One of the most interesting is that of the German mathematician Gottfried Wilhelm Leibniz (1646–1716). As librarian to the Elector of Hanover, Leibniz was professionally concerned with building up libraries, but he also had a substantial collection of at least 6000 books of his own – a further 3000 were the subject of a dispute between his heirs and the Elector. This library is now housed, along with Leibniz's extensive papers, in the State Library of Lower Saxony in Hanover; the printed volumes, whose margins contain many annotations, are still relatively unexplored.[52]

The collection formed by Samuel Pepys (1633–1703) is a well-known survival from this period. Pepys's 3000 volumes were bequeathed to Magdalene College, Cambridge, on terms that permitted no books to be added or removed, and they remain in their original presses virtually as Pepys left them. His library, however, reflected his position as Secretary of the Admiralty and President of the Royal Society (from 1684 to 1686) rather more than a thoroughgoing pursuit of scientific knowledge. Pepys nevertheless owned collections of the works of his most important scientific contemporaries, such as Boyle, Hooke and Newton, as well as material relating to his particular interests in navigation, geography and hydrography.[53]

The fate of the library of John Evelyn (1620–1706) provides a cautionary example and a sad contrast to that of Pepys, his friend and fellow virtuoso. Evelyn's library was larger than Pepys's and much more significant in terms of scientific books – the product not only of wealth, membership of the Royal Society and social contacts with the leading natural philosophers of Restoration England, but also of a serious interest in fields such as chemistry, botany,

zoology, anatomy and medicine, and especially horticulture and forestry. A catalogue drawn up in 1687 records nearly 5000 books and pamphlets, on a wide variety of subjects, including some 350 works on mathematics and music, 240 on medicine, 200 on philosophy and 160 'Historiæ Materiarum & Œeconom. Rei Rustici Mechanologici &c.' Towards the end of Evelyn's life, however, shortage of space forced him to dispose of a substantial number of volumes; further books were sold or removed (notably by the nineteenth-century collector William Upcott) over the centuries in which the library remained in the possession of the Evelyn family. By 1951, when the library was placed on deposit at Christ Church, Oxford, only some 2000 volumes remained and this residue included many books of Evelyn's time that had been purchased more recently. Items from Evelyn's own collection could often be distinguished, however, by their bindings, or by the presence of shelfmarks or other inscriptions in his hand, such as his motto 'Omnia explorate, Meliora retinete'. The sales of 1977–78 marked the final stage in their dispersal, although the British Library fortunately acquired some 300 volumes, choosing to concentrate mainly on those with Evelyn's annotations. Among them were his heavily marked set of *Philosophical Transactions* and a number of presentation copies of works by Robert Boyle. Taken together with Evelyn's commonplace books, catalogues and working papers, now also at the British Library, these volumes make it still possible to investigate in detail the ways in which Evelyn used his library.[54]

More often, of course, book collections made in the sixteenth and seventeenth centuries have long ago been scattered in all directions. In the absence of documentary evidence, a careful reconstruction, using the provenance indexes of institutional libraries (incomplete though these usually are), may be the only possible means of discovering the contents of a particular individual's library.[55] Generally this depends on the presence of signatures or distinctive marks of ownership, though sometimes a pattern of subsequent ownership may be sufficient to establish the original provenance. Isaac Newton, for example, rarely wrote his name in his books, and did not have a bookplate, but most of his library later passed into the possession of Charles Huggins and then of James Musgrave: Newton's books, now widely dispersed, may often be identified by the bookplates of these two men and by comparison with the probate inventory drawn up soon after his death in 1727. Although this document is the principal source for the contents of Newton's library, it listed some items collectively and omitted others; the reconstruction of the library using the additional evidence of surviving volumes has supplemented this.[56]

Examination of individual volumes may provide considerable additional information not only about the scientific preoccupations of the owner, but also about his habits as an owner of books. Newton is again an interesting example because as well as sometimes annotating volumes that he owned, he more frequently turned down the corners of pages to mark particular passages. This practice may be observed in about a third of the nearly 900 volumes from his library preserved at Trinity College, Cambridge.

An author's reading (if not, necessarily, the books he owned) may sometimes be inferred from the bibliographical citations in his published work; manuscript annotations in printed books may also occasionally be so extensive as to constitute evidence of this sort. This is of particular importance if little is otherwise known of the reader's views. The copies of Bacon's *Sylva Sylvarum* (1631) and Thomas Browne's *Pseudodoxia Epidemica* (1646) that belonged to Christopher Wren (1591–1658), ejected Dean of Windsor and father of the architect and scientist, are annotated with many references to Wren's scientific reading, including works by Tycho, Kepler, Copernicus, Gesner and Gassendi, as well as to his own acute observations of the world around him. Wren's interest in science was known from his biography in *Parentalia*, but the annotations, which indicate parallel interests to his son and to his son-in-law William Holder, demonstrate the intellectual vitality of his family circle in Oxford in the 1650s.[57]

In some cases, such marginal annotations were indeed later printed as commentaries on the text. Perhaps the most celebrated scientific example concerns the copy of Diophantus, *Arithmetica* (Paris, 1621), owned and annotated by the mathematician Pierre de Fermat (1601–65). Fermat's copy has been lost, but his marginal notes were printed *verbatim*, after his death, in the Toulouse edition of 1670. These included the tantalising statement that he knew how to prove the theorem which has since become famous as 'Fermat's last theorem' – and remained unproved for centuries – but did not have space in the margin to write the proof down: 'Hanc marginis exiguitas non caperet.'[58]

Another potentially fruitful approach to the history of scientific libraries is to investigate the provenance of as many copies as possible of a particularly important or interesting work. As yet, this approach has been pursued in relation to Copernicus' *De Revolutionibus* (1543), Galileo's *Dialogo* (1632 and 1635) and Newton's *Principia* (1687), but it could usefully be applied more widely, since it promises to shed light not only on numerous otherwise unknown owners but also on patterns of distribution and price, on a work's reception at different times and the various ways in which it could be read and annotated. In the case of the works already mentioned, the owners included many famous scientific names, reflecting in part the process of presentation and exchange of books, as well as a number of individuals who were well known as scholars or the owners of large libraries, but not necessarily associated with scientific interests. In the latter category, for example, *De Revolutionibus* was owned by Giuseppe Zarlino, the Venetian theorist of music, by Juan de Herrera, architect of the Escorial, by the antiquary William Camden, by the banker Johann Jakob Fugger and by Saint Aloysius Gonzaga, as well as by John Aubrey, Tycho Brahe, Giordano Bruno, Thomas Digges, Galileo and Kepler. Newton's *Principia* was owned by Fellows of the Royal Society such as Martin Folkes, Samuel Pepys, John Aubrey, Flamsteed, Locke and John Wallis, but also by others who have not been readily identified.[59]

At present, however, most of the published studies of sizeable scientific book collections before about 1720 are concerned with the libraries of individuals

who are already known for their scientific interests – some have already been mentioned and it is to some other British examples that the rest of this survey will be addressed.[60] Even in the case of some of the most famous scientists, unfortunately, the surviving evidence about their libraries may be fragmentary and potentially misleading. Robert Boyle's library, for instance, which was large by the standards of the time, even though it does not seem to have impressed Evelyn, has disappeared almost without trace. No catalogues or inventories recording the contents of the library are known to survive, nor is it clear how the books were dispersed. A newspaper advertisement of July 1692 announced that Boyle's library would be sold at Lady Ranelagh's house, where 'any Gentlemen or Others, may have the opportunity to View, and Buy what they please, at reasonable Rates.' It would seem, however, that this sale was abandoned, for by March 1693 some of the books had reached an open-air secondhand book market: Robert Hooke's diary recorded 'neer 100 of Mr Boyles high Dutch chymicall books ly exposed in Moorfields on the rails.' Later the same month the auction catalogue of the library of Silvanus Morgan, an arms-painter, sold on 5 April 1693, also included 'the *Latin* Part of the Library of an Honorable Gentleman, lately deceased, consisting of Divinity, History, Geography, &c. The whole are generally gilt on the back many of them of the Large Paper curiously adorned.' Hooke's diary identifies these as Boyle's books, but they were not separately listed in the catalogue and there is only inconclusive evidence as to which these may have been. Only a small number of books from Robert Boyle's library are now known, mainly because they contain presentation inscriptions from their authors.[61]

Scientific libraries in Britain: Sir Thomas Smith to Sir Hans Sloane

The development of the study of science and mathematics in England was closely associated with the revival of interest in Greek studies in the late fifteenth and early sixteenth centuries. Corrupt Latin versions were abandoned in favour of the Greek originals, or new translations, and in this way the corpus of ancient science was established on more accurate textual foundations. Among the most influential advocates of Greek studies were Sir John Cheke, who in 1540 became the first Regius Professor of Greek at Cambridge, and Sir Thomas Smith (1513–77), the first Regius Professor of Civil Law and a Fellow of Queens' College, Cambridge. Smith's accomplishments as a mathematician and astronomer were celebrated after his death by Gabriel Harvey, who described him as greater than Ptolemy and a hundred Alfonsos. A catalogue of Smith's library, dated 1 August 1566, shows him to have possessed many important astronomical works, by Gemma Frisius, Regiomontanus, Stoeffler and Apian, as well as a copy of Copernicus' *De Revolutionibus* and works by Archimedes, Euclid and Ptolemy. The list is also interesting because of its division into very broad subject categories: astronomy, architecture (Vitruvius), geometry, cos-

mography and navigation are grouped under 'Mathematica', while 'Philosophica' embraces medicine, metallurgy, military science, zoology, ornithology, agriculture and the occult.[62]

Probably the most remarkable scientific library of sixteenth-century England was assembled at Mortlake by the astrologer, astronomer and mathematician John Dee (1527–1608 or 1609). Dee, a protégé of Sir John Cheke, played an important part in promoting the study of science in the English language, as an alternative to the tradition of the universities; his lengthy 'Mathematicall Praeface' to the first English translation of Euclid (1570) gives some impression of how he used his own very large collection of some 3000 printed volumes, as well as manuscripts relating to medieval science, alchemy, astrology, astronomy, physics, geometry, optics and mathematics. Dee's library catalogue, studied in detail by Roberts and Watson, provides extensive evidence of his interests and working methods: Greek mathematical texts, notably of Archimedes, are well represented, while the list of Dee's holdings of Euclid almost amounts to a bibliography in its own right of the sixteenth-century editions. The coverage of more recent mathematical works, both in Latin and vernacular languages, was outstanding: Dee owned works by the French mathematicians Finé and Ramus, as well as Italians such as Cardano and Luca Pacioli. His collection of works on astronomy was also remarkable: Ptolemy was well represented, while Dee owned two copies of the 1543 edition of Copernicus' *De Revolutionibus*. There were substantial groups of books relating to mining and metallurgy, to botany and to medicine.

Most of Dee's books were printed abroad, and his catalogue therefore provides some evidence of the availability of these specialized foreign works in England – Dee owned, and presumably ordered from, catalogues published for the international Frankfurt book fairs during the 1570s. Many other books, however, were acquired by Dee himself on his travels, which included visits to Bohemia and Poland. Some surviving books from the library have been traced, including alchemical works with numerous annotations in Dee's hand. Another important aspect of this great collection was that, while it remained at Mortlake, it served as a focal point for scientific studies in England and was used not only by Dee himself, but also by a circle of his friends and pupils.[63]

Dee's library invites comparison with another very large collection, the library built up by John, Lord Lumley (c. 1534–1609), with the encouragement and assistance of the physician, antiquary and geographer Humphrey Lloyd (1527–68). Lumley's library, which included books inherited from Henry Fitzalan, Earl of Arundel (d. 1579), also amounted to about 3000 items, with particular strengths in history, medicine, navigation, travel and cosmography – in the last of these fields, it was perhaps the finest personal collection to be formed in Tudor England. Recorded in the Lumley catalogue of 1609 are works on mathematics, astronomy and astrology by Ptolemy, Aristotle and Euclid, Copernicus, Regiomontanus, Peurbach, Sacrobosco, Stoeffler, Apian, Cardano, Finé and Postel, as well as alchemical writings by Arnaldus de Villa Nova, Ramón Lull

and George Ripley. After Lumley's death, the collection passed into the royal library and later into the British Museum; about 1350 of these books are now known to remain in the British Library and some 150 others have been traced elsewhere.[64]

One of the recorded visitors to Dee's library was Sir Walter Ralegh (1552?–1618), a shelf-list of whose books – some 500 volumes – survives from a period near the end of his life. The collection listed was very wide-ranging, but included works on geography, cosmography and astronomy, as well as a group of books on chemistry, which was a particular interest of Ralegh during his imprisonment, when he built his own still in the Tower of London.[65] A fellow-prisoner there, who conducted experiments with Ralegh, was Henry Percy, ninth Earl of Northumberland (1564–1632), known as the 'Wizard' Earl because of his interests in science, magic and alchemy. Northumberland was outstanding among English virtuosi of the early seventeenth century, and his library, estimated at between 1500 and 2000 volumes, was one of the most important personal collections of its time. Several hundred surviving volumes have been identified, including a number with annotations in the Earl's hand. Among the scientific books were two which he apparently read as a boy: French editions of Holywood's *De Sphaera Mundi* and Peter Apian's *Cosmographia*, edited by Gemma Frisius. Northumberland owned works by Gilbert, Kepler and Tycho Brahe; he had an extensive collection of the works of Paracelsus; other groups of books which he might have considered broadly scientific were concerned with the art of war, fortification and architecture. His household accounts show that even during his imprisonment he continued to purchase the most recent continental publications on subjects such as mathematics, alchemy and medicine from London booksellers who specialized in importing foreign books and who visited the Frankfurt fair. Within Northumberland's household, furthermore, were the three 'Magi', the natural philosopher Thomas Harriot (1560–1621), the mathematician Walter Warner, and the geographer Robert Hues, to whom he granted pensions. The same household accounts also include Harriot's bookseller's bills for the period 1617–18; among the recorded purchases of this correspondent of Kepler, were (appropriately) Kepler's *Epitome Astronomiae Copernicanae* (1618), Snell's *Observationes* (1618) and Quir's *Terra Australis Incognita* (1617), together with the Frankfurt fair catalogues from which these had been selected.[66]

More scientific collections survive from the middle of the seventeenth century and some of these migrated to the American colonies. One example is the alchemical library of John Winthrop (1606–76), first governor of Connecticut and the son of the founder of the Massachusetts-bay Colony. Winthrop was famous throughout colonial New England as a chemist and practitioner of chemical medicine; this practice was based on an extensive collection of books, which also included alchemy, occult philosophy, astronomy, metallurgy, natural history and mathematics. When Winthrop arrived in Boston in 1631, he already owned about a thousand volumes; his papers provide interesting evidence of the ways in which he was able to continue to build up his collection at a distance by

correspondence with friends, agents, London and continental booksellers and merchants. A particular feature of his collection was that many items were acquired, by gift or exchange, from the libraries of others well known for their scientific interests, notably John Dee (probably through Dee's son, Arthur) and the alchemist Robert Child.[67]

Geographical isolation appears to have been rather more of a problem for the medical practitioner and controversial critic of the universities John Webster (1611–82), of Clitheroe in Lancashire. Webster's library catalogue records a substantial and valuable collection of some 1600 volumes, of which a very high proportion, some 40 per cent, were concerned with natural philosophy and medicine. These included the works of Descartes and Bacon, a large group of Aristotelian commentaries and textbooks, as well as works in the very different tradition of Alsted and Comenius: Webster's catalogue provides ample evidence of his eclectic approach. Alchemy and hermetic learning were well represented; there were 15 volumes of Paracelsus alone, with many others by his followers. Over a hundred volumes related to occult science. Webster's interest in astronomy was reflected in his ownership of major works by Copernicus, Galileo and Kepler, as well as related items by authors such as Ismael Boulliau and John Wilkins; his mathematical holdings included not only Euclid and other ancient texts, but also works by his contemporaries, Isaac Barrow, John Wallis and William Oughtred. Relatively few items in the catalogue, however, date from after the Restoration; Webster withdrew to Clitheroe in the mid-1650s and his subsequent correspondence suggests that latterly he borrowed more books, notably from Martin Lister, than he bought for himself.[68]

Other parts of the British Isles supported flourishing scientific communities by the late seventeenth century. The libraries of two members of the Dublin Philosophical Society, for instance, are well documented. William Molyneux (1656–98), the first Secretary of the Society, had the means to amass a substantial library of some 2000 volumes, mostly on scientific subjects: his correspondence makes numerous references to the acquisition of books, including instructions to his brother Thomas to buy books for him at auction in Holland in the 1680s. The strengths of William Molyneux's library lay especially in astronomy and optics, his main interests, but most contemporary scientific authors were well represented, including Bacon (about 50 volumes), Boyle, Descartes, Gassendi, Grew, Hooke, Newton, Wilkins and Willis. The library catalogue of the first Director of the Dublin Philosophical Society, the physician Charles Willoughby, lists some 800 volumes, including works by Bacon, Boyle, Descartes, Galileo, Hooke, Kepler and Newton, as well as medical works by Harvey, Sydenham and Thomas Willis. A number of the Society's other members, as well as friends of Molyneux and Willoughby, are recorded as borrowers from these libraries, a process by which continental scientific publications played a full part in Dublin's intellectual life.[69]

The mathematician Isaac Barrow (1630–77), Master of Trinity College, Cambridge, has been described as 'an excellent specimen of a seventeenth-century

bibliophile'. Barrow's collections profited from his friendship with his fellow mathematician John Collins, who put his bibliographical knowledge, his considerable experience of the London book trade and his extensive network of foreign correspondents at Barrow's disposal. Barrow wrote to Collins: 'I love to have by me divers books, which I do not much esteem, upon which score you need not scruple at your discretion to send me any book that I have not. I never matter the point of money in this case ... 'tis hard if there be not one thing at least to be learned out of any new book, and that satisfies me more than the expense of a few shillings can displease me.' In spite of – or perhaps because of – this approach to book-buying, Barrow's collection was a celebrated and relatively select one, from which Newton among others was able to borrow. Known from the catalogue prepared after Barrow's death, the library appears to have amounted to about 1000 volumes: about 330 of these related to medical or scientific subjects, of which almost half were concerned with mathematics.[70]

A larger mathematical collection was formed by Sir Jonas Moore (1617–79), Surveyor General of the Ordnance, who was instrumental in the foundation of the Royal Observatory. Moore's interests in astronomy, practical mathematics, land-surveying, navigation and cartography were reflected in his library of over 2000 volumes, about half of which was broadly concerned with these subjects. Moore had expressed an intention to bequeath his mathematical books to the Royal Society, but died intestate. Despite efforts to persuade the universities of both Oxford and Cambridge to buy the library as a whole, the books were sold by auction in November 1684. The rare survival of an annotated copy of the printed auction catalogue, now in the British Library, provides evidence of a lively and wide-ranging community of mathematical book-buyers. Among the purchasers at this sale were Edward Bernard, the Savilian Professor of Astronomy at Oxford, John Flamsteed, the first Astronomer Royal, physicians such as Hans Sloane and the surgeon Charles Bernard, Robert Hooke, Edmond Halley, Edward Pagett, the Master of the Royal Mathematical School in Christ's Hospital, Sir Edward Sherburne, also of the Ordnance Office and translator of Manilius, and teachers of applied mathematics such as Venterus Mandey and George Sinclair.[71]

By the late seventeenth century, London offered a wide range of opportunities to the collector of scientific books. The man who probably took fullest advantage of these was Robert Hooke (1635–1703), a figure of central importance within the Royal Society whose contribution to English science is discussed elsewhere. It is clear from Hooke's diaries that the pursuit of books was his principal recreation and an activity that took up a substantial part of his time. The diaries record a daily round from bookshop to coffeehouse, his calls on the principal publishers of scientific works, and his frequent visits to Moorfields and Duck Lane to scour the secondhand shops and open-air stalls of cheap and old books. Hooke was also a regular purchaser at book auctions and participated actively in the culture of intellectual and social exchange within the international scientific community, both giving and receiving publications and allowing others to borrow his books.[72]

Hooke's library offers some evidence to suggest an increased specialization, even professionalisation, of scientific book collecting, which is perhaps also apparent in connection with the development of auction catalogues as a new marketing device. The auction catalogue of Hooke's own books, sold in 1703, listed over 3000 volumes, most of them scientific and medical: there were also good collections of architecture, of geography, and of bibliographical reference material, but noticeably little theology. Hooke owned an extensive collection of sixteenth-century scientific works, by authors such as Copernicus (the second edition of *De Revolutionibus* (Basle, 1566)), Euclid, Ptolemy, Regiomontanus, Cardano, Finé, Giordano Bruno and Paracelsus. His holdings of corresponding material for the seventeenth century were virtually complete, including major works by Boyle, Gilbert, Kepler, Galileo, Huygens and Hevelius, together with Newton's *Principia*. A particular selling point, emphasised in the preface to the auction catalogue, was that Hooke was 'not a bare Idle Possessor of them, he hath left behind him many curious Notes on some, considerable MSS Improvements to others, not unworthy the View and Perusal of the Virtuosi of the Age.'

The library of Sir Isaac Newton (1642–1727) remained in private hands, unnoticed, for some 200 years after Newton's death, before being sold in two segments in 1920 and 1928: many of his books are now preserved in Trinity College, Cambridge. Newton's library, consisting of some 2100 volumes, belonged, arguably, to an older tradition than that of Hooke. It was the working library of a scholar whose interests were by no means limited to what are now considered scientific subjects. Theology, Biblical criticism and chronology bulked as large as natural philosophy: each comprised about 30 per cent of the books. It was also the library of a scholar who used other libraries, notably the personal collection of Isaac Barrow (Newton went on to acquire some of Barrow's books after his death in 1677), as well as the collections of the Public Library (as the university library in Cambridge was then known) and Trinity College. It is therefore even more difficult than usual to draw conclusions from the apparent weaknesses of Newton's own scientific holdings: there was relatively little medicine or astronomy, for instance, and many of the great names of mathematics and physics are also conspicuously absent. What is noteworthy, however, is the sizeable proportion (about ten per cent) of Newton's books that was concerned with alchemy. Newton owned as many books on alchemy as he did on mathematics: he had nine works by the German alchemist Michael Mayer, eight by Ramón Lull, and four by the Benedictine monk Basil Valentine. Newton appears to have set out to build up this alchemical collection systematically, making use of bibliographies such as Pierre Borel's *Bibliotheca Chimica* (Paris, 1654) and William Cooper's *A Catalogue of Chymicall Books* (London, 1675–88).[73]

The library of Sir Hans Sloane (1660–1753) marks a turning-point in the history of personal scientific collections in England. Sloane's collections up until the 1690s appear to have had much in common with the substantial libraries built up in this period by other medical men, such as Francis Bernard and

Richard Mead, which have not been discussed in detail here. As a young man, who had studied medicine in Paris and Montpellier, Sloane purchased books to support his own professional and scientific interests: the strengths of his collection were in medicine, botany and zoology, geography and travel. In 1689, he returned to London, after two years as physician to the Governor of Jamaica, and settled into a successful medical career; in 1693, he was elected Secretary of the Royal Society. A detailed study of the chronological development of Sloane's library catalogues has suggested that by about this time he had acquired over 3000 printed books and about 25 manuscripts. This substantial library was supplemented by a collection of curiosities and natural history specimens that was already attracting notice.

During the 1690s, Sloane's horizon as a collector lifted. In part this was no doubt due to an increased income from his fashionable medical practice, and a good marriage (in 1695), as well as the opportunities offered by the auction sales for buying up ready-made collections – Sloane owned some 700 book auction catalogues, both English and continental. By 1698, the number of manuscripts in his collection had increased to more than 300, while the printed books numbered some 10,000 volumes. Sloane's collecting was no longer directed towards supplying his own needs, but began instead to take on an omnivorous institutional scale, which required assistance from librarians as well as an impressive array of bibliographical reference tools. An example of the latter was Sloane's copy of G.A. Mercklin's edition of the medical bibliography by J.A. van der Linden, *Lindenius Renovatus, sive De Scriptis Medicis* (Nuremberg, 1686). This work was interleaved, bound up in eight volumes and copiously annotated with press-marks and addenda. In the early 1700s, in common with some other collectors, Sloane also developed an interest in the antiquarian aspects of book collecting: he was buying books because of their printing history and collecting medieval scientific and alchemical manuscripts.

In the course of his career, Sloane was President of the College of Physicians (1719–35), succeeded Newton as President of the Royal Society (1727–41), and was appointed physician-general to the army and first physician to George II. These positions brought him not only a fortune, but also contacts and a foreign correspondence which he could exploit in pursuit of books. He was able to spend very large sums of money very effectively over a long life. On his death in 1753, his executors were instructed to offer his entire collection to the nation for the sum of £20,000. This challenge was met by setting up a lottery and founding the British Museum. By the time of their arrival at Montagu House, Sloane's collections included – in addition to several thousand plants, vegetables, insects, fishes, shells, precious stones, fossils and metals, prints, coins and medals – a library containing some 4000 manuscripts and 45,000 printed books. The greatest library in England of its time, this was also the last encyclopaedic scientific library to be assembled in England by one man.[74]

Notes

1. John Evelyn to William Wotton, 29 March 1696; cited in Hunter, Michael (ed.) (1994), *Robert Boyle by himself and his friends*, London: Pickering, p. 88. Cf. Adrien Baillet, *La Vie de Monsieur Des-Cartes* (Paris, 1691), ii. 467.
2. For the background, see Hunter, Michael (1981), *Science and Society in Restoration England*, Cambridge: Cambridge University Press, chapter 6; Webster, Charles (1975), *The Great Instauration: science, medicine and reform 1626–1660*, London: Duckworth.
3. Thomas Sprat, *The History of the Royal-Society of London* (London, 1667), p. 97.
4. Diary of an unnamed divine (possibly Zachary Merrill), 1 April 1692: Bodleian Library, Oxford, MS Rawlinson D. 1120, f. 62v. Cited by Maddison, R.E.W. (1969), *The Life of the Honourable Robert Boyle*, London: Taylor & Francis, p. 198. For the fate of Boyle's library, see below.
5. *The Record of the Royal Society of London*, 4th edn, London: Royal Society, 1940, pp. 298–9. Cf. Hall, Marie Boas (1992), *The Library and Archives of the Royal Society, 1660–1990*, London: Royal Society, p. 2. Robert Hooke's view was that the library of the Royal Society should contain 'all books of Arts and Naturall History and of noe other whatsoever'. For the debate over the role of the Society's library and of the non-scientific books within it, see Hunter, Michael (1989), *Establishing the New Science*, Woodbridge: Boydell Press, especially chapter 6, and Linda Levy Peck (1998), 'Uncovering the Arundel Library at the Royal Society: changing meanings of science and the fate of the Norfolk donation', *Notes and Records of the Royal Society of London*, vol. lii, pp. 3–24. For John Evelyn's ambitious proposal for forming a library, drawn up in 1661 for Sir Robert Moray, President of the Royal Society, see Keynes, Geoffrey (1968), *John Evelyn: a study in bibliophily*, 2nd edn, Oxford: Clarendon Press, pp. 17–19.
6. See, for example, the correspondence of Henry Oldenburg (?1615–77), first Secretary of the Royal Society and editor of *Philosophical Transactions*: Hall, A.R. and M.B. (eds), *The Correspondence of Henry Oldenburg*, 13 vols, Madison & Milwaukee: University of Wisconsin Press, 1965–73; London: Mansell, 1975–7; London: Taylor & Francis, 1986.
7. Feingold, Mordechai (1997), 'The mathematical sciences and new philosophy', in Tyacke, Nicholas (ed.), *The History of the University of Oxford*, vol. iv, *Seventeenth-century Oxford*, Oxford: Clarendon Press, esp. pp. 397–409.
8. McKitterick, David (1986), *Cambridge University Library: a history*, vol. ii, Cambridge: Cambridge University Press, p. 95.
9. See, for example, *Travels of Cosmo III, Grand Duke of Tuscany, through England, during the reign of King Charles the Second* (1821), pp. 291–93, cited by Maddison, pp. 143–44.
10. Feingold, Mordechai, (1991) 'John Selden and the nature of seventeenth-century science', in Bienvenu, Richard T. and Feingold, Mordechai (eds), *In the Presence of the Past: essays in honor of Frank Manuel*, Dordrecht/Boston/London: Kluwer Academic Publishers, pp. 55–78. Selden's books are now in the Bodleian Library, Oxford. For another example, cf. the astronomical, mathematical and geographical books of Archbishop Ussher of Armagh, now in the library of Trinity College, Dublin: Boran, Elizabethanne (1998), 'The libraries of Luke Challoner and James Ussher, 1595–1608, in Robinson-Hammerstein, Helga (ed.), *European Universities in the Age of Reformation and Counter-Reformation*, Dublin: Four Courts Press, pp. 75–115.
11. Harrison, John and Laslett, Peter (1971), *The Library of John Locke*, 2nd edn, Oxford: Clarendon Press, pp. 1, 23–25. Cf. Clericuzio, Antonio (1993), 'Medicina,

chimica e filosofia naturale nella biblioteca di John Locke', in Canone, Eugenio (ed.), *Bibliothecae Selectae da Cusano a Leopardi*, Florence: L.S. Olschki, pp. 333–75. Many of Locke's books are now in the Bodleian Library.

12. See, for example, Houghton, Walter E. (1942), 'The English virtuoso in the seventeenth century', *Journal of the History of Ideas*, iii, pp. 51–73, 190–219; Hunter, Michael (1982), *The Royal Society and its Fellows 1660–1700: the morphology of an early scientific institution*, Chalfont St Giles: British Society for the History of Science; Hunter, *Science and Society*, chapter 3. Cf. Impey, Oliver and MacGregor, Arthur, *The Origins of Museums*, Oxford: Clarendon Press, and Turner, Anthony (1987), *Early Scientific Instruments*, London: Sotheby's Publications.
13. Davis, Natalie Zemon (1983), 'Beyond the market: books as gifts in seventeenth-century France', *Transactions of the Royal Historical Society*, 5th series, 33, pp. 69–88; Findlen, Paula (1991), 'The economy of scientific exchange in early modern Italy', in Moran, Bruce T. (ed.), *Patronage and Institutions: science, technology, and medicine at the European court 1500–1750*, Woodbridge: The Boydell Press, pp. 5–24. For the archetypal virtuoso library, that of John Evelyn, see Keynes, *John Evelyn: a study in bibliophily*, and the auction sale catalogue, *The Evelyn Library*, London: Christie's, 22 June 1977 to 13 July 1978.
14. See, for example, the arithmetic manuals described in Smith, David Eugene (1908), *Rara Arithmetica*, Boston & London: Ginn; Davis, Natalie Zemon (1960), 'Sixteenth-century arithmetics on the business life', *Journal of the History of Ideas*, vol. xxi, pp. 18–48; Gordon, Cosmo (1916), 'Books on accountancy, 1494–1600', *Transactions of the Bibliographical Society*, vol. xiii for 1914, pp. 145–70; Taylor, E.G.R. (1954), *The Mathematical Practitioners of Tudor and Stuart England*, Cambridge: Cambridge University Press; Taylor, E.G.R. (1930), *Tudor Geography*, London: Methuen; Taylor, E.G.R. (1934), *Late Tudor and Early Stuart Geography*, London: Methuen; Fussell, G.E. (1947), *The Old English Farming Books from Fitzherbert to Tull, 1523 to 1730*, London: Crosby Lockwood; Eamon, William (1994), *Science and the Secrets of Nature: books of secrets in medieval and early modern culture*, Princeton: Princeton University Press; Heninger, S.K. (1969), 'Tudor literature of the physical sciences', *Huntington Library Quarterly*, vol. xxxii, pp. 101–33 and 249–70.
15. Munby, A.N.L. (1968), *The History and Bibliography of Science in England: the first phase, 1833–1845*, Berkeley & Los Angeles: The University of California, p. 1.
16. Glomski, Jacqueline (1996), 'Book collecting and bookselling in the seventeenth century: notions of rarity and identification of value', *Publishing History*, xxxix, pp. 5–21; Viardot, Jean (1988), 'Naissance de la bibliophilie: les cabinets de livres rares', in Jolly, Claude (ed.), *Histoire des Bibliothèques Françaises*, vol. ii, *Les bibliothèques sous l'Ancien Régime 1530–1789*, Paris: Promodis, pp. 268–89.
17. Munby, A.N.L. (1952), 'The distribution of the first edition of Newton's *Principia*', *Notes and Records of the Royal Society of London*, vol. x; reprinted in his *Essays and Papers*, London: Scolar Press, 1977, pp. 43–54.
18. Gabriel Naudé, *Advis pour dresser une Bibliothèque* (Paris, 1627), chapter iv. Also translated as *Advice on Establishing a Library*, with an introduction by Archer Taylor, Berkeley & Los Angeles: University of California Press, 1950. For a much more extensive bibliography published later in the seventeenth century, see Cornelius à Beughem, *Bibliographia Mathematica* (Amsterdam, 1688). For other examples of early bibliographical guides, see Blum, Rudolf (1980), *Bibliographia*, Folkestone & Chicago: American Library Association & Dawson; Taylor, Archer (1945), *Renaissance Guides to Books*, Berkeley & Los Angeles: University of California Press; and Taylor, Archer (1966), *General Subject-Indexes since 1548*, Philadelphia: University of Pennsylvania Press.

19. Samuel Hartlib, John Dury, John Pell and their circle, for example, attached considerable importance to the role of libraries and devised various plans for making better use of them: see John Dury, *The Reformed Librarie-Keeper* (London, 1650); Webster, Charles (ed.) (1970), *Samuel Hartlib and the Advancement of Learning*, Cambridge: Cambridge University Press; and Turnbull, G.H. (1947), *Hartlib, Dury and Comenius*, Liverpool: University Press of Liverpool. For John Evelyn's elaborate schemes for the arrangement of his own library, divided and sub-divided 'according to the Intellectual Powers', see Keynes, *John Evelyn: a study in bibliophily*, pp. 13–17, and de la Bédoyère, G. (1994), 'John Evelyn's library catalogue', *The Book Collector*, vol. 43, pp. 529–48.
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24. Rose, pp. 36–56; Grafton, Anthony (ed.) (1993), *Rome Reborn*, Washington, New Haven & London: Library of Congress & Yale University Press; Labowsky, Lotte (1979), *Bessarion's Library and the Biblioteca Marciana*, Rome: Edizioni di storia e letteratura.
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26. Rose, p. 46; Sánchez Mariana, Manuel (1993), *Bibliófilos Españoles*, Madrid: Biblioteca Nacional, pp. 37–8; Hobson, Anthony (1970), *Great Libraries*, London: Weidenfeld & Nicolson, p. 159; Graux, Charles (1880), *Essai sur les Origines du Fonds Grec de l'Escurial*, Paris: Bibliothèque de l'Ecole Pratique des Hautes Etudes, fasc. 46.
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31. Howard, Rio (1983), *La Bibliothèque et le Laboratoire de Guy de La Brosse* (Geneva: Droz, *Histoire et Civilisation du Livre*, xiii, 1983).
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33. Costabel, P. (1975), *Florimond de Beaune (Blois, 1601–1652), 'Doctrine de l'angle solide'; inventaire de sa bibliothèque*, Paris: Librairie Philosophique J. Vrin.
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39. *DNB*; Feingold, p. 58. An edition of Rainolds's catalogue is being prepared by Mordechai Feingold.
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45. Robert Clavell, *The General Catalogue of Books, Printed in England ... to the End of Trinity-Term MDCLXXX* (London, 1680), preface.
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Chapter Eleven

Scientific Book Collectors and Collections, Public and Private, 1720 to Date

Judith Overmier

A collector writes that some of his books collected him, another that he began to build his collection of rare science books modestly, still others that they planned from the start to collect all the great science books. The words have a friendly and familiar ring. The voices of collectors and collections speak through published collection catalogues, exhibit and sale catalogues, through books and articles about collectors and collections and about a collection's uses and users, through annual reports and collecting correspondence. These sources are written by those who wish to share their pleasure and fascination with individual books and with collections that are greater than the sum total of the individual books they contain by describing and interpreting them for others. The voices address scientists, historians, librarians, book dealers, book collectors, students, scholars – all of whom may experience the sciences by degree, by inclination, by practice, by admiration, by awe.

Collectors exist along continua. They may be wealthy or of average means; they may be highly educated, science enthusiasts or scientists. They may be forming a working scientist's collection or a bibliographer's or a bibliophile's. They may collect science as part of a general collection or as a specialized collection; it may be all of science they are collecting or individual disciplines, such as chemistry, mathematics, physics, astronomy, geology, or combinations thereof.

Since the nineteenth century rare science books have been increasingly collected by individuals and by libraries for bibliophilic or for historical purposes

rather than as scientists' working collections. More and more frequently librarians and collectors see rare science books as access points to the history of science, and the history of science as an access point to the sciences for the average person. The historical records of collecting have grown concomitantly during this period and often we can study the collectors' comments on why they collected, on how they developed their subject scope over time, on where they acquired their books, and on how and why they disposed of their collections. Recognizing the importance of science and the history of science, many collectors and libraries published catalogues and other information about their collections; as a result some collections are well known, even those that have been dispersed, inherited, donated or sold. Other collections remain little known, with no voice, because there were few or no publications about them.

Collections have been identified for use in writings by Thornton and Tully, by Munby, and most recently by Wells. Wells published an international list of those scientists collecting rare books. She identified most of the 880 scientists' collections from the published catalogues, usually sale catalogues, of their collections. Many of these scientists collected in areas other than science and the majority of the scientist collectors were physicians. Only 240 were mathematicians, botanists, chemists, naturalists, astronomers, zoologists, engineers, geologists or physicists (Wells 1983). Her work confirms that the number of scientist collectors of rare science books is not large. The pool of non-scientist collectors of rare science books is even smaller.

During the twentieth century librarians have provided voice to rare science books by describing related books in clusters of library collections[2] or 'conceptual collections'[3] by identifying in a printed source rare science titles embedded in larger non-specialized collections. Collectors, librarians and archivists have begun to collect in ways that parallel the earlier collecting of scientists' papers that accompanied book collections but extend it further to expand the record of the history of science through the introduction of 'documentation strategy'. This concept of organized archival collecting and preservation of the papers of twentieth-century science, such as laboratory notebooks, personal papers and professional papers, extends and enriches the historical record.

A glimpse of the variety of science libraries built since 1720 should begin with the eighteenth-century private collections built by notable scientists and by informed amateurs. The collecting voice of Thomas Pennant (1726–98), naturalist and zoologist, provides an eighteenth-century example of a scientist building a working library of natural history and topography books. Rees and Walters (1970) comment on the appropriateness of Pennant's autobiography opening with the receipt of a gift of Francis Willughby's *Ornithology*.[4] They characterize Pennant's correspondence in the National Library of Scotland and National Library of Wales as full of love of both natural history and book collecting. His correspondence with Peter Simon Pallas[5] is also full of books; Pallas often looked for books for Pennant and other scientists. Pennant's collection sold at auction in 1913; it contained copies of his own works and

copies of books given to him (with manuscript notes) as well as those that he had collected.

Another eighteenth-century example of a working science library is that of Joseph Priestley (1733–1804). He acquired books in support of his scientific research and his history of science research. His volume on the history of optics included an appendix listing books that he owned, as well as others that he had used. His correspondence and contacts within the scientific community brought him many books from his colleagues. Legal records list 50 of the approximately 350 titles that were destroyed in the burning of Priestley's house and laboratory in 1791 by a mob.[6] Leaving England three years later Priestley settled in Pennsylvania, bringing books with him, including a 200-year-old alchemical manuscript.[7] Several scientific journals and an additional 350 books were identified by Eric Robinson[8] from a 1782 list of Priestley's library contents that Robinson found while working with the papers of James Watt (1736–1819). Robinson laments that there still is no complete bibliographical record of the entirety of Priestley's library, a record – or voice – that scholars desire for the collection of every scientist.

Sir Joseph Banks (1743–1820) was an advocate of scientific activities, a 'pervading influence' in science.[9] He collected approximately 10,000 natural history books, with an emphasis on botany, and another 3500 on the other sciences. His library took ten years to catalogue and the resulting publication (*Catalogus Bibliothecae*) appeared in five volumes from 1800 through 1805. Banks began collecting while a student; it is reported that his first book was Gerard's *Herbal* (1597). Banks' trip to Holland in 1773 intensified his collecting and by 1777 he had become an avid collector. His correspondence reveals a sophisticated collector who acquired books from bookshops, catalogues, book dealers and publishers, and as gifts from authors; he even circulated *desiderata* lists. Banks published pamphlet catalogues in the years before his main catalogue was published. The catalogues were undoubtedly useful to those scientists wishing to use his collections, which he generously made available. Banks willed his library to the British Museum.[10]

In America during this same time period Thomas Jefferson (1743–1826) was an influential supporter of science and an amateur scientist. Jefferson was a book collector with wide interests and his library has been catalogued in five volumes by Sowerby.[11] Abrahams documents Jefferson's special interest in science and science books, which Jefferson purchased for his library.[12] His collection was very strong in chemistry, reflecting his own interest in that particular science. Abrahams lists the chemistry books, which are part of Jefferson's library that survived as part of the third of his entire library that still exists. Jefferson's library of about 6000 volumes was purchased in 1815 by the US government.

Benjamin Smith Barton (1766–1815), the Philadelphia physician and naturalist, also a bibliophile, reportedly collected actively until his death. He owned 372 natural history titles, with the oldest dated 1512. He acquired his books

mostly by purchase, but also as gifts from colleagues. His collection was dispersed; 126 are in the library of the American Philosophical Society.[13]

One of the largest private collections of the period was that of Alexander von Humboldt (1769–1859). His was a working collection that grew to approximately 15,000 volumes. Archival correspondence uncovered by Helmut De Terra[14] documents that after Humboldt's death various attempts were made to sell his extensive library to institutions and individuals in America. Humboldt's long-term strong ties with the American scientific community would seem to have made this a possibility had the book collection been offered separately from a considerable amount of other material and at an appropriate price. Eventually Henry Stevens (1819–86), an American bookdealer, purchased the collection, sold portions of it and auctioned portions of it.[15] During this process, some part of the collection was destroyed by fire. The auction catalogue lists, but does not fully describe, the collection.

Peter Mark Roget (1779–1869), best known for his thesaurus, was active in the scientific community most of his life. He belonged to many scientific associations, so that his working library of materials related to the developing scientific fields of that period was rich in journals. He had 1732 scientific volumes in his library of 4089 volumes, books being the exception to Roget's non-collecting propensities according to his biographer Emblen.[16] Roget's collection was dispersed at auction (1870) after his death; Emblen[17] has detailed its contents and the prices reached.

Not all collectors acquired books on the broad range of the sciences. Many worked from a general base and then focused on specialized areas of science. Mathematics books were one popular area of collecting. The library of John Playfair (1748–1819), the mathematician, was sold at auction after his death. He had collected 1400 volumes of the major works of general science, the largest portion being mathematics. His collection also contained geology; this point is of particular interest[18] because of Playfair's unexpected activity in the field.

The astronomer Stephen Peter Rigaud (1774–1839) also collected mathematics books, along with physics and astronomy. He is remembered for his collection, although there are no well-known publications to give it voice. In fact, in 1934 and 1935 R.T. Gunther had to campaign to keep Rigaud's library altogether at Oxford, even publishing a plea for its preservation in *Nature*.[19] The campaign met with no success, those books retained at Oxford were dispersed and the remainder were sold at auction.[20] Rigaud is better recalled for his knowledge of the literature and history of astronomy and for the collection of the correspondence of scientific men of the seventeenth century that he was editing at the time of his death. His son completed it and Augustus De Morgan (1806–71), the collector of mathematics books, re-edited it in 1822.

The mathematician Charles Babbage (1792–1871) collected a working library of over 2500 titles. Although it was strongest in mathematics, with 799 titles, it also contained books on astronomy, mechanics, optics and electricity. Those

subject areas combined more than equalled the mathematics titles as listed in the auction catalogue.[21] Babbage's library was purchased in 1872 by James Ludovic Lindsay (1847–1913), the 26th Earl of Crawford, to develop the science portion of his family's library. He later donated those science books, along with additional titles that he acquired using the catalogue of the library of the Pulkovo Observatory as a buying guide, to Scotland to be the core of a library for a new national observatory.[22] At the time the collection was transferred in the 1890s it had 15,000 books, including manuscript books, 80 incunabula, 450 sixteenth-century, 600 seventeenth-century, and over 1000 eighteenth-century books. Macdonald and Morrison-Low (1994) compiled *A Heavenly Library*,[23] the catalogue of an exhibit featuring the treasures of the Crawford Collection, which is still part of the library at the Royal Observatory in Edinburgh.

George Peacock (1791–1858) was another collector of science and mathematics books.[24] His collection, which sold at auction on 7 December 1858, was particularly strong in mathematical incunabula. His books, 342 lots of them, were completely dispersed and now it is even difficult to locate a copy of the auction catalogue.

Augustus De Morgan (1806–71), the mathematician and prolific author of scientific works and popular works of science, was, like his former tutor George Peacock, a collector of mathematical works. His volume *Arithmetical Books From the Invention of Printing to the Present Time* (1847) was based entirely on books that he had actually examined, most of them in his own collection. His later editors and biographers have commented on his bibliographical scholarship. David Eugene Smith, an American mathematics book collector of the next generation, wrote in the preface to the second edition of *Budget of Paradoxes* (1915) that he admired De Morgan, worked in De Morgan's library, and continued De Morgan's bibliographical work. Even De Morgan's obituary noted that he knew about watermarks, colophons and catchwords. Sophia Elizabeth De Morgan, his wife, speaks in her *Memoir* (1882) of her husband of his 'keen interest in books and their history' and of his passion for collecting rare books, which he began collecting shortly after leaving Cambridge. In the 'Introductory' to his *Budget of Paradoxes* (1847) De Morgan lists the sources of the books discussed in it as purchased in shops, individually at auction, and as bonus titles in lots at auction. He writes that he received them as gifts or as review copies or unexpectedly found them bound-in with other titles. No doubt he practised these methods for all the books he collected. Recent scholarship[25] on De Morgan provides specific examples of the important role such gift books, for example a 1489 arithmetic from John Bellingham Inglis or an 1700 arithmetic from James Orchard Halliwell, played in De Morgan's historical research. After his death 3000 of his remaining books, annotated and extra-illustrated as was his habit, were purchased by Lord Overstone (1796–1883) and presented to the University of London.

An equally knowledgeable collector contemporaneous with De Morgan, the mathematician and historian of science Guglielmo Libri (1803–69), so marred his collecting history that he is remembered today largely as a colourful book

thief, rather than as the informed, scholarly collector that he could have been. At various times during his career Libri had access to Italian and French libraries as a researcher and eventually in France as a government inspector of libraries and as a member of the official government commission that was preparing a catalogue of manuscript holdings of French libraries. Among the approximately 90,000 books and manuscripts that he collected legitimately were thousands that he stole. How many exactly is unknown, except for the 1900 manuscripts that he sold to the Earl of Ashburnham.[26] He also sold thousands of books at auction over a sixteen-year period, for which he produced a number of high-quality descriptions for the catalogues (for example the sale catalogue of 1861: see Catalogue in bibliography).

The textbook publisher George Arthur Plimpton (1855–1956) collected educational works on a large, broad scale and eventually donated more than 13,000 books and several hundred manuscripts to Columbia. Plimpton thought mathematics was one of the most important parts of a general education and his donation was strong in pre-1600 arithmetics, with more than 300 titles. Plimpton described his collection in a presentation at the International Mathematical Association meeting in Bologna, Italy, 6 September 1928.[27] The collection was thoroughly catalogued by his friend David Eugene Smith (1860–1944), who often bought books for Plimpton's library while on buying trips for himself.

Smith donated his own 10,000–volume collection of mathematical works to Columbia in 1931 and then endowed it at his death.[28] In addition to his mathematics books he also collected astronomical and calculating instruments. Smith made a number of contributions to the history of mathematics; for example, he taught the history of mathematics, using his collection as a teaching tool. His description of George Arthur Plimpton's books in *Rara Arithmetica: a Catalogue of the Arithmetics Written Before the Year MDCI With a Description of those in the Library of George Arthur Plimpton of New York* (1908) is particularly full, even including content summaries. The catalogue was aimed at students of the history of mathematics. He wrote the introduction to the bicentenary volume on evaluation of Newton's work and the first chapter, 'Newton in the light of modern criticism', for *History of Mathematics* (1928).

Chemistry books also had their specialized collectors. James Young (1811–83) was a collector from Glasgow who wrote that he collected not as a working scientist's collection or for pleasure, but with the intent that students and researchers use the books in the study of the history of science and chemistry. He began collecting in 1850 and eventually acquired about 1400 books and pamphlets that were catalogued by another collector of chemistry books, John Ferguson (1838–1916). Ferguson wrote full descriptions of the books, including biographical notes about authors and content summaries, for the two-volume *Bibliotheca Chemica* (1906) so that the catalogue would be educational per Young's wish for the collection. Ferguson was one of the early collectors to assert that books were no longer available for collecting.

Henry Carrington Bolton (1843–1903) also collected chemistry in that time period. He was active in book-collecting circles and exhibited his books at the Grolier Club in 1891. A catalogue was prepared for the exhibit, *Catalogue of Works on Alchemy and Chemistry*, which displayed 606 books. Bolton provided historians with collecting evidence by annotating all his books with their purchasing history.[29] Bolton also compiled his *Select Bibliography of Chemistry, 1492–1892*, which despite its title was comprehensive, as well as supplements to it in 1899 and 1903. In the bibliography, Bolton indicates the books in his private library with an asterisk.

The chemist Edgar Fahs Smith (1854–1928) was actively interested in the history of chemistry all during his career. He published widely in the history of chemistry and in his lectures to students on the topic Smith emphasized the 'environment of the chemists and their time' and made it a point to cover the 'overshadowed' chemists. He used his 1000 rare chemistry books as examples during his lectures and eventually gave the collection to the University of Pennsylvania along with endowment funds to continue its development.[30]

The collector Denis I. Duveen (1910–96?) wrote in the preface to the catalogue of his collection, *Bibliotheca Alchemica et Chemica: An Annotated Catalogue of Printed Books on Alchemy, Chemistry and Cognate Subjects* (1949) that the catalogue recorded the results of his long 'affliction with bibliophilia or, as some would have it, bibliomania'. The classic bibliographic tool in the field prior to Duveen's catalogue was Ferguson's catalogue of the Young collection, which was strong in sixteenth- and seventeenth-century works. Duveen's collection was stronger in eighteenth- and nineteenth-century works, so he published his catalogue to increase the level of bibliographic access for students in the field. His collection of about 2000 titles was acquired by the University of Wisconsin Libraries in 1951 and it stimulated acquisition in that area.[31] The library's collections were so strong in the area that in 1965 it published a catalogue[32] listing all its books printed before 1800 on the subjects chemistry, medicine and pharmacy. After publishing his catalogue, Duveen bought more books to build a second library. The collection had a history of chemistry focus and included more American chemistry. This second library was sold in 1953 through the Kraus catalogue 629. Duveen sold the collection because he had decided his collecting scope was too broad. He therefore limited his scope to Lavoisier and promptly built yet another collection. He exhibited this third collection at the Grolier in 1952 and two years later published his bibliography of Lavoisier, followed twelve years later in 1956 with a supplement. Duveen's Lavoisier collection is now at Cornell University.

A lesser-known library of chemistry books was collected over a 25-year period by Joseph Wayland Morgan, a retired chemistry professor, who presented his 1200 books, pamphlets, photographs and periodicals to the library of Ohio University. Roger W. Moss, Jr compiled a catalogue of the gift, *The Morgan Collection in the History of Chemistry: A Checklist*, in 1965.

The collector William A. Cole collected the major and minor works of eighteenth- and nineteenth-century chemistry for over 30 years. His bibliography (1988) of the collection, *Chemical Literature 1700–1860* (see bibliography), has 1393 entries, with full descriptions that include provenance information and biographical information about the authors. Cole's purpose was to trace the history of chemistry, so he acquired multiple editions, which he says he bought for an historical record of changes and additions, and he purchased translations for information about how ideas were 'accepted, interpreted or modified in other countries'. His collection was partially dispersed to the Huntington and the University of Wisconsin. The latter Cole allowed to purchase only those it did not already own. Cole continues to add to the collection by gift.[33]

A series of collectors of rare books on electricity and magnetism has provided England and the United States with outstanding historical resources in these areas. The earliest of these collectors was Sir Francis Ronalds (1788–1873), an inventor and meteorologist. The *Catalogue of Books and Papers Relating to Electricity, Magnetism, the Electric Telegraph, &c. Including the Ronalds Library* (1800) is still an important bibliographic tool for collectors and historians in the field.

Ronalds was followed by Josiah Latimer Clark (1822–98), who had a successful career as an electrical engineer. He collected comprehensively in the areas of magnetism, electricity, galvanism and on the telegraph. His pamphlet collection is considered unsurpassed. Although he collected from his mid-twenties, most of his collection was acquired from 1858 to 1898. Clark, a friend of Ronalds, knew that Ronalds' collection would be in England, so he wanted his collection to go to America to provide historical resources there. This was made possible by Schuyler Skaats Wheeler (1860–1923), an electrical engineer, who acquired the Clark collection and donated it to the American Institute of Electrical Engineers in 1903. The *Catalogue of the Wheeler Gift* (1909) provides a record of the collection at that time, including those works that Wheeler added to it. The latter are marked in the catalogue, which has extensive annotations for its 7000 titles because of its educational goal. The building in which the library was housed and the cataloguing of the collection were funded by an Andrew Carnegie donation. The Engineering Society gave the Wheeler Gift to the New York Public Library in 1995.

The Bakken, a non-profit educational research centre since 1976, began in 1969 as a private collection. Earl Elmer Bakken (1924–), an electrical engineer and inventor of the first wearable cardiac pacemaker, became interested in the historical roots of his field and established his collection in the tradition of the great electrical and scientific rare-book collectors of the nineteenth century. The library acquired 10,000 books, journals and manuscripts on the history of electricity and magnetism in life, many of which are recorded in *Books and Manuscripts of the Bakken* (1992). The collection is comprehensive, including the biological and life sciences and health and even the humanities, if electricity is involved. The Bakken's main intent is to further ' ... the understanding of the

history, cultural context, and applications of electricity and magnetism in the life sciences and their benefits to contemporary society'.[34]

The Babson Institute (later Babson College), founded by Grace Margaret Knight Babson (1873–1956), wife of Roger W. Babson (1875–1967), has a large collection of Newton. A catalogue of the collection, *A Descriptive Catalogue of the Grace K. Babson Collection of the Works of Sir Isaac Newton*, was published in two volumes in 1950–53, followed by a supplement in 1955. The collection has played a continuing role in the collecting and educational communities. For example, on 25–26 November 1927, meetings and the opening of an exhibit for the Bicentenary of the death of Sir Isaac Newton (1642–1727) were held at the American Museum of Natural History. The exhibit included works from the Babson Institute Library, as well as from the collections of David Eugene Smith and George A. Plimpton. In addition to all the editions and translations of Newton's works and works about them, the Babson Institute provides a working history of science collection by acquiring related primary books and bibliographies, biographies and histories. Grace K. Babson's collection of Newton's works was transferred from Babson College to permanent deposit at the Burndy Library at the Massachusetts Institute of Technology in 1995. In keeping with the collection's educational goals, an exhibit and a two-day symposium on Isaac Newton's philosophy marked the occasion.

Robert Stewart Whipple (1871–1953) was another collector of that period who intended that his books be used for educational purposes. He had a lifelong professional involvement and personal fascination with scientific instruments and their history. That led to his collecting 1500 rare science books as well as instruments, all of which he donated to the University of Cambridge in 1944. The occasion was marked with an exhibit that autumn, and in 1994 an anniversary exhibit focusing on astronomy books from 1478–1600 was mounted in Cambridge's Whipple Museum of the History of Science. The exhibit's catalogue *Sphaera Mundi* (1994) provides a voice for this outstanding collection.

In 1941 Frederick Edward Brasch (1875–1967), collector, librarian and bibliographer, established at Stanford University a collection on Sir Isaac Newton and the History of Scientific Thought with the gift of 1500 volumes on Stanford's 50th anniversary. By 1987 and the exhibit in honour of the tercentenary of the publication of Newton's *Philosophiae naturalis principia mathematica* (1687), there were 4000 volumes on Newton, influences on Newton, and Newton's influences on the other sciences. Astronomy interested Brasch throughout his life and although he collected in other areas of science, it was this interest that stimulated his Newton collecting. Brasch recalls that his first book, J. Dorman Steele's *A Fourteen Weeks Course in Descriptive Astronomy* (New York, 1869) was purchased around 1895 for 25 cents. Brasch collected books his entire life and planned from mid-life to donate his collection to Stanford.[36] In 1948 Brasch went to Stanford as consultant and then curator of the Newton Collection. He was an experienced science librarian, working at the John Crerar and then as assistant chief and later chief of the Smithsonian Division of the Library of

Congress (later named the Science Division). Cole writes that Brasch believed that the study of the history of science was important and that reading the writings of early scientists was a good way to approach the field. Brasch's own scholarship was historical and bibliographical; an example of the latter was his survey[37] locating and describing American, Canadian and Mexican copies of Newton's *Principia.* Brasch wrote that he did this research following up on an idea of the collector David Eugene Smith. Brasch's papers and his family papers are at Stanford.

There are over 1000 pre-1800 volumes in the Herbert Clark Hoover Collection of Mining & Metallurgy: Bibliotheca De Re Metallica in the Honnold Library at The Claremont Colleges in California. Herbert Clark Hoover (1874–1964), engineer, began collecting in 1908 and within the next seven years had acquired 573 books. In 1912 he purchased the first edition of *De Re Metallica*, and although he collected other sciences too, geology is the largest portion of the collection. The collection's published catalogue, *The Herbert Clark Hoover Collection of Mining & Metallurgy: Bibliotheca De Re Metallica*, contains 912 entries. His family donated his books in 1970, and the collection is housed in Honnold Library, named after William Lincoln Honnold (1866–1950), mining engineer and friend of Hoover. The *De Re Metallica*, which played such an important role in the development of this collection, was translated by Herbert Clark Hoover and his wife Lou Henry Hoover (London, 1912). They began collecting the mining and metallurgy books to assist in the translation and understanding of *De Re Metallica* and continued to expand from there.[38] Although Hoover's interest in rare books had begun while he was a student at Stanford, he felt he could not afford such books. When he did begin to buy, he bought books abroad, in London in particular, where he and his wife had a house. He collected in several other subject areas as well, developing major collections there too. Hoover's book-collecting correspondence is part of the Honnold Library collection.[39]

The library of the University of Reading houses the collection built by Francis Joseph Cole (1872–1959). Cole's research career in marine zoology, comparative anatomy and zoology expanded to include history, bibliography and bookcollecting in biology and medicine. His publications included historical articles and volumes, such as his *History of Comparative Anatomy, From Aristotle to the Eighteenth Century* (1944) and his 'History of Albrecht Durer's rhinoceros in zoological literature' (1953).[40] Cole began collecting in 1889 and at the age of 85 he, by then owner of over 8000 books, referred to himself as a 'zoo-bibliophile'.[41] In that article, 'Obiter Dicta Bibliographica', he wrote knowledgeably and with good humour about his collecting ups and downs. He was one of the many collectors over the years who thought it was no longer possible to develop collections such as his own because the books were all becoming part of institutional libraries and because the prices had become prohibitive for the average collector. All of his writing was informed with bibliographical nuances. He reports of Darwin's 1859 *Origin*, for example, that the first issue requires a

misprint on page 20, line 11. The breadth of his knowledge in this arena and his concern for its importance is evident in his article 'Bibliographical reflections of a biologist'. Nellie B. Eales, who catalogued his library, approached the volumes at the same sophisticated level, both in the published catalogue[42] and in her article discussing the provenance features of selected volumes from the collection.[43] The University of Reading's pleasure in acquiring Cole's collection after his death in 1959 is demonstrated in its *Nature* announcement (1960), which lists the highlights of the collection.

Chester Hjofdur Thordarson (1867–1945) a Chicago electrical manufacturer was a private collector known for his 'collecting energy'.[44] He acquired 11,000 volumes of rare science and technology works to show the growth of British science and technology, but within a larger context than this description implies.[45] His collection was built mainly between the wars. Lagana[46] highlights the impetus the purchase of this collection in 1946 by the University of Wisconsin had in the development of the study of the history of science and of the library collections in that field at Wisconsin, where it reinvigorated the history of science programme which had been established in 1941; it was the first independent department of the history of science in the United States.

The anatomist Herbert McLean Evans (1882–1943) wrote that he 'spent all his savings and one or two small inheritances upon good copies of the original or first editions of the really great things in each of the nine sciences (mathematics, astronomy, physics, chemistry, geology, botany, zoology, medicine)'.[47] He was one of the earliest, most remarkable and most influential of the twentieth-century collectors of rare science books. He earned this status because of his exhibit for the 94th annual meeting of the American Association for the Advancement of Science, 18–24 June 1944, and the exhibit catalogue *Exhibition of First Editions of Epochal Achievements in the History of Science* he prepared for it, because of his gregarious interactions with other collectors, librarians and book dealers, and because of the enormity and intensity of his book-collecting abilities that resulted in the building of seven collections. Over a period of 37 years Evans' collections went to the Institute of Advanced Study at Princeton, to the Denver Medical Society, to collectors Sam and Cecile Barchas, to the University of Chicago, and to the University of Texas at Austin. Others were redistributed to collectors such as Bern Dibner and Everett Lee De Golyer through bookdealers and their catalogues.

Rare science books covering the fields of natural sciences, chemistry and alchemy, physics, botany, zoology and astronomy comprise a portion of the notable book collection of Erik Waller (1875–1955). Waller, a surgeon and an avid collector of books on medicine and the history of medicine, built a collection of 21,000 books. Most of these were medical in nature, but 2000 were in what the catalogue of his collection refers to as the allied sciences. He gave his collection to the library of the Royal University of Uppsala, which prepared a printed catalogue of the entire collection.[48]

Everette Lee DeGolyer (1886–1956) reportedly collected almost 89,000 books in several different subject areas during his lifetime.[49] He had begun collecting

seriously in 1941, but it was not until 1948 when Conant's book *On Understanding Science* piqued his interest in the history of science that he first spoke of the University of Oklahoma Libraries as a home for a proposed collection of rare science books.[50] DeGolyer was an experienced collector when he purchased his first rare science book, Galileo's *Dialogo* (Florence, 1632) while in Italy on a business trip. He wrote to a friend that his trip 'yielded some priceless finds for the library collection' and that since his return he had acquired some classics, such as a first edition of Copernicus.[51] The first books from DeGolyer arrived at the University of Oklahoma in November 1948. DeGolyer had made the transfer of his collection contingent on the University's establishing a department of the history of science and the University made its first appointment toward that goal in 1954. Duane H.D. Roller (1920–94), the first faculty member and curator of the collection, began developing the collection in 1954 with the expressed intent of acquiring everything published and was remarkably successful in his efforts. The collection went through a period of rapid growth from 1949 through 1956, followed by several decades of continuing support during which the library added about 2000 books a year. A catalogue of the library listing 40,000 printed volumes was published in 1976.[52] The library, now titled the History of Science Collections and holding approximately 86,000 volumes, continues its development at the University of Oklahoma.

'Modestly at first, then with increasing confidence (and recklessness) each of the important classics of science were purchased', wrote Bern Dibner (1897–1988), an electrical engineer, who began as a personal collector and founded the Burndy Library, which was soon incorporated in 1941 as a private non-profit educational organization. The library already had 5000 to 6000 pre-1900 books even though he had only begun collecting in 1936[53] and his collecting goal soon became the classics representative of all the sciences and in electricity and magnetism 'every purchasable item prior to 1900'.[54] Dibner built a remarkable collection including over 300 scientific incunabula. His success in acquiring the most significant works in the history of science was recorded in the first edition of *Heralds of Science* in 1955 and the second edition in conjunction with the Smithsonian in 1980. In *Rare Books and Special Collections of the Smithsonian Institution* (1995), Wells and Overstreet describe Dibner's role in the 1976 formation of the Dibner Library of the History of Science with a gift of 8000 books from the Burndy Library that Dibner had formed in Norwalk. It was the Smithsonian's first rare book library and is located in the National Museum of American History. Dibner has enabled the Smithsonian to continue to develop its active history of science program, publishing *Manuscripts of the Dibner Collection* (1985) which describes 1614 groups of manuscripts, sponsoring an annual endowed lecture and a resident scholar programme. Like many other collectors, Dibner built a new collection after he had presented much of the first one to the Smithsonian.[55] That second Burndy Library was relocated in 1992 to the Massachusetts Institute of Technology where it established the library of the newly developed Dibner Institute

for the History of Science and Technology, a consortium formed by MIT, Boston University, Brandeis and Harvard.

Albert Edgar Lownes (1899–1979) collected in other fields before focusing on science.[56] He started in college, first collecting local floras of New England, and eventually expanding to collect all of science. He left about 12,000 books to Brown University, his alma mater.[57] Lownes exhibited books from his collection at Dartmouth for the 1970 meetings of the New England Renaissance Society and then at Wellesley. In the preface to the exhibit catalogue *Renaissance Books of Science, From the Collection of Albert E. Lownes* (1970) he wrote 'For half a century I have tried, within my means, to find the great books of science ... ' but 'It is the secondary and tertiary books that give color to collecting and make it fun.' Of those latter books he wrote 'Of course, I tell myself, I don't collect these books; yet here they are. Sometimes I think they collect me'. In the introduction to the exhibit catalogue David Godine wrote that Lownes' collection 'reflects his enthusiasm for the mundane as well as the celebrated' and that only Lownes' ' ... energy, imagination, and a healthy amount of stubborn determination could have amassed so outstanding and comprehensive a collection'. In addition to exhibiting his books, Lownes lectured about them, participated in the collecting community, and opened his collection to researchers. He interacted with science book collectors Herbert Evans and Bern Dibner and used Evans' *First Editions of Epochal Achievements* as a collecting guide. Lownes coordinated his personal collecting with Brown and other local institutional libraries. He wrote 'When I began to think of Brown as a possible recipient of my books, I changed my collecting policy. If Brown or any other Providence Library had a copy of a rare book, I did not try to acquire it'.[58]

Harrison D. Horblit began collecting right after college and collected science because it was, 'a field not appreciated'.[59] The preface to the Sotheby sale catalogue of 10–11 June 1974 of his collection said his interest was 'Deriving from its owner's passionate interest in sailing', and that 'it began as a collection of navigational books – many of outstanding rarity – and spread outward to embrace astronomy, navigation's natural corollary, then mathematics, physics, and virtually every branch of science'. Horblit made his collection available for scholarly use[60] and was active in the collecting community. He organized *One Hundred Books Famous in Science*, an exhibit at the Grolier Club during Spring of 1958. Horblit corresponded with Dibner, Wheatland, Honeyman and rare book dealers during the preparation of that exhibit.[61] His collecting focus changed in the 1970s and he began disposing of his collection of rare science books. The Sotheby sale of the books was discontinued and his books were later sold by H.P. Kraus beginning with Catalogue 168, which had 207 entries on the history of science, including navigation, from Horblit's library.

David Pingree Wheatland (1899–1993) knew books and his collecting field very well and was active in the collecting community, exhibiting some of his books in the Grolier Club exhibit of famous science books. He began collecting books on electricity and magnetism in the 1930s and although no record of

his entire collection exists,[62] he did have prepared in 1971 a 265-page, bound typescript catalogue titled *Electricity and Magnetism Before 1820 and Other Scientific Books: Short-Title List of a Collection Formed by David P. Wheatland* for that portion of his collection.

Robert B. Honeyman (1898–1983) began collecting in the 1920s. An engineer and metallurgist, graduate of Lehigh, he collected in several areas, including science. He donated many books to Lehigh, starting in 1929. Honeyman's books in combination with several other donations over the decades made one of Lehigh's strong areas rare science books.[63] In 1959 he gave Lehigh a large collection of Darwin books, a number of which were proof copies, including the only known proof copy of *The Origin*. That same year he sent a desiderata list to Zeitlin writing 'bring to my attention any of the great books in the history of science that come your way'.[64] Honeyman's collection was planned as 'a complete picture of the development of scientific thought and practice'.[65] It took nine looseleaf volumes to record his entire collection,[66] which included nearly one hundred scientific incunabula. Honeyman sold his collection at Sotheby's in London in a series of seven catalogues from 1978 through 1981 (*The Honeyman Collection of Scientific Books and Manuscripts*).

Libraries, even small ones, are as cognizant of the role that science and the history of science now play in society as individual collectors are, and libraries want their special science collections or the strength of the science holdings in their general collections known. *Early Scientific Books in Schaffer Library, Union College* (1971), the catalogue prepared by Wayne Sommers, lists pre-1800 science publications in the library in 1971. Brooke Hindle's introduction gives a detailed history of the development of the library from 1795. It had around 800 volumes by 1800 and the college and the library had a science emphasis in those early years. It purchased books in Albany, New York, Philadelphia and then in Europe. The rare books were separated out into a special rare book collection in 1971. Volume two of Wightman's *Sciences and the Renaissance* is *An Annotated Bibliography of the 16th Century Books Relating to the Sciences in the Library of the University of Aberdeen* (Aberdeen, 1962) that fills the same function for that larger university.

The historical development of the John Rylands University Library of Manchester's strengths in the history of science are delineated in a recent article by John V. Pickstone. He highlights the rare books and introduces us to the rich archival and manuscript papers of nineteenth and twentieth-century scientists such as astonomers Zdenek Kopal (1914–) and Sir Bernard Lovell (1913–). Like many university libraries, there is no printed catalogue to describe the science materials located in various sites, but several exhibit catalogues focusing on specific areas of science have been published. They and Pickstone's article provide the necessary voice for science books and archives.

The idea of an exhibit entitled *Milestones of Science: Epochal Books in the History of Science ...* that covered the most important works of science from Copernicus to 1900 arose at the Buffalo Society of Natural Sciences in 1937.

The books for the exhibit were collected from May to April 1938, a first edition of Copernicus being the first book purchased according to the exhibit catalogue. This remarkable collection of books remained in a static state in the Museum's library until the autumn of 1996 when it moved to the Grosvener Rare Book Room in the Buffalo and Erie County Public Library. Although the collection is not expected to begin acquiring titles at its new site, it does grow in a different way. The collections at the Buffalo and Erie County Public Library already contained considerable complementary material and the *Milestones* titles are now being catalogued. These factors will increase its usefulness and accessibility to scholars.[67]

The Linda Hall Library in Kansas City was endowed by Herbert Hall (–1941) and named after his wife. It opened in 1946 and intended from the start to become a major independent research library. The board that was set up to establish the library decided on science and technology as its collecting focus. The following year, 1947, the Linda Hall Library purchased the Library of the American Academy of Arts and Sciences which had been in existence since 1780 and which by 1947 had accumulated collections rich in resources for the history of science. The Linda Hall Library has continued to build its overall collections and a number of endowments given since its founding have ensured the growth of the historical materials. It was able to purchase books from the Honeyman sale, for example. And in January 1995 the Engineering Society Library New York, New York transferred to the Linda Hall in Kansas City, Missouri 350,000 volumes dating from 1493. Throughout its five decades the Linda Hall has established a strong educational role and in recent years has been very active in programming and exhibits.[68]

Even humanities libraries participate in creating bibliographic tools to access their history of science resources. Jean Gottlieb's *Checklist of the Newberry's Printed Books in Science, Medicine, Technology, and the Pseudosciences, ca 1460–1750* is the published record of what she has named a 'conceptual collection'. That library collection's strengths end in 1750 (p. xi).

Electricity, Magnetism, and Animal Magnetism: a Checklist of Printed Sources 1600–1850, compiled by Ellen G. Gartrell (1975), exemplifies the idea of publishing a guide to a 'cluster' collection created by identifying related resources in several different libraries. In Gartrell's volume the libraries are in Philadelphia and included are the American Philosophical Society, the Library Company of Philadelphia, the College of Physicians of Philadelphia, the University of Pennsylvania, the Franklin Institute and the Historical Society of Pennsylvania.

The broadening of collecting formats in the history of science has resulted in such other publications as *Sources in Electrical History: Archives and Manuscript Collections in US Repositories*, which describes 1008 collections in 158 repositories. It is based on an earlier work and took several years to prepare under the auspices of the Center for the History of Electrical Engineering.

The Franklin Institute and its library were founded in 1824. The library was established with a donation of science books and the collection grew through

gifts, purchases, and the exchange programme that was so common in that time. Some gifts were notable, such as Orville Wright's aeronautical engineering collection. At the time of its dispersal in 1985 the library had become a major source in science and the history of science and was providing service to its members and to the general public. The library was sold in parts in a series of auctions and sales.[69]

The John Crerar Library, which was established in 1897, joined the University of Chicago in 1984. Crerar's will endowed a free public library and the trustees determined that the library would focus on science, technology, and medicine. In 1967 it held nearly 600,000 titles. Its various educational activities included an exhibit of 95 works with a printed catalogue, *Science Through the Ages* (1978).

Sources of Science and Technology: An Exhibit of One Hundred and One Books and Documents Showing the Development of Physical Science, Mathematics and Technology in the West (1972) celebrated the collection of John D. Stanitz. An engineer whose field was fluid dynamics, Stanitz began collecting the physical sciences, machinery, mathematics and technology in 1951. He wrote that the first book he bought was Bernoulli's *Hydrodynamica* which he purchased from Brentanos rare book department in Chicago. As his collection developed he refocused it and sold at auction a few books that did not fit within his new collecting scope. Eventually he sold his entire collection at Sothebys (1984).

Samuel I. and Cecile M. Barchas ' ... conceived of a collection that would bring together leading works of Western Science, in, whenever possible, their earliest printed editions, works that both laid the groundwork for and described the major discoveries of Western scientific tradition'.[70] They began with a 1791 edition of Ferguson's *Astronomy Explained Upon Sir Isaac Newton's Principles* and focused on astronomy. They then expanded into math and physics; in 1961 they bought the fifth of Herbert Evans' seven collections.[71] They collected for 35 years, acquiring 5000 volumes, 2000 of which were rare books, including the 100 famous science books from the Grolier Club exhibit.[72] When Sam and Cecile Barchas transferred their books to Stanford, they were considered ' ... the finest general history of science collection remaining in private hands in the United States'.[73] An exhibit and exhibit catalogue, *The Barchas Collection: the Making of Modern Science* (1985), were prepared for the celebration of the dedication of a named reading room.

In 1991 the exceptional catalogue of the collection of the psychiatrist Haskell F. Norman (1915–96) was published. It contains complete bibliographic descriptions, extensive, erudite annotations, and indexes to authors, subjects, artists, binders, and provenance for the 2600 items described. Previously a 123–entry exhibit catalogue with equally exacting bibliographic standards was published for the International Congress of Bibliophiles (1985). It covered science from the fifteenth to the early twentieth century, with a section of 28 American entries. Haskell Norman, in his introduction to the Freud exhibit

catalogue published in 1991, briefly discusses his evolution as a collector and documents the development of the scope of his collection. That introduction is extended into a full-blown essay on his 'education as a bibliophile' in his collection catalogue.[74] He writes that his first purchase was of Freud's *Die Traumdeutung* (1900) in 1953 and that a decade later in 1963 he purchased his Vesalius (1543). None of his books were purchased for use, even his psychiatry books; he was always a collector. Norman writes that he began with dealer catalogues and correspondence and only later visited bookstores or knew other bibliophiles, collecting associations and dealers. He credits the dealer Ernst Weil with introducing him to presentation copies and special bindings and taking him to his first auction. From Warren Howell in San Francisco he reports he learned more about condition and Norman maintained the practice of improving his copies. Norman was a very sophisticated collector acquiring not only significant scientific works but 'special' copies, such as the author's copy, dedication copies, presentation copies, association copies, copies in special bindings, and variants. Norman's collection, the most extensive collection of rare science books that remained in private hands, is being dispersed at auction by Christies.[75]

Three examples of organized archival collecting within a discipline are the Othmer Library of Chemical History of the Chemical Heritage Foundation, the Niels Bohr Library, Center for the History of Physics of the American Institute of Physics, and the Archives, Special Collections and Documentation Department of the Deutches Museum. The Othmer Library was founded with a $5 million challenge grant from Dr. Donald F. Othmer (1904–95) and his wife Mildred Topp Othmer. The Chemists' Club of New York presented the first gift, 8500 volumes, and also loaned the Othmer Library 500 rare chemistry books. The Othmer Library has grown to 30,000 volumes, pre-1930 and established archival collections of chemists' correspondence, laboratory notebooks and so on, and has acquired the archives of several chemical societies. In addition the library's oral history collection has over 100 interviews. The Othmer Library is part of the Chemical Heritage Foundation which was established in 1983 and encourages 'research, scholarship and popular writing in the history of chemical sciences and chemical process industries'.[76]

The Niels Bohr Library, Center for the History of Physics, American Institute of Physics has established a documentation strategy that calls for a 'non-collecting' archival centre for the field. It does collect its own archives, of course, but its goal is to record the existence of other archival collections and to collect microfilm copies of other collections when possible. It also plays an important role in encouraging and assisting other agencies in developing their archives and it does sometimes house homeless archives until such time as an appropriate plan is developed to care for them. The Niels Bohr Library creates and collects oral histories and maintains photo archives, such as the Emilio Segre Visual Archives. The library collects sources for biography, history, philosophy and sociology of physics, historical technical publications, nineteenth- and twentieth-century texts, laboratory manuals, and equipment catalogues.

The Deutsches Museum's archival and special collections unit houses extensive collections. In addition to library collections and institutional archives it houses the private papers of over 200 individuals active in the fields of science and technology. It also maintains the archives of scientific institutions and societies and of manufacturing companies that have conducted scientific and technological research. It has a very large, 160,000-item, collection of trade literature, an historical resource which is often difficult to locate.[77]

A private collection incorporating elements of the new collecting approaches was formed by Jagdish Mehra (1935–). The Jagdish Mehra Collection was acquired in 1995 by the Special Collections and Archives Department of the University of Houston Libraries. It focuses on physics, astrophysics, cosmology, mathematics and the history of science and includes 15,000 monographs, photographs, manuscript copies of published and unpublished works of scientists, oral history interviews and transcripts, and the correspondence of twentieth-century physics. Mehra collected these materials, often interviewing the scientists himself, and he continues to develop the collection.

Although various collectors and dealers have commented since the nineteenth century on the shortage of rare science books on the market or on their disappearance into institutional collections, they have nevertheless been successfully collected throughout the twentieth century, and private collectors and collecting opportunities do still exist. One traditional rare book collection still in private hands is that of the mechanical engineer Verne Louis Roberts (1939–). In *Bibliotheca Mechanica* (1991), the catalogue of his collection, he and Ivy Trent have written detailed descriptions, historical notes, provenance notes, and locations of other copies of the books. In 150 copies of his catalogue he has provided a frontispiece printed from an original copper engraving from the third edition of Newton's *Principia*.

In addition to such traditional collections, one can see the extension and broadening of the definition of formats to be collected from manuscripts, books and journals to include archival materials and computer files. This is once again increasing the level of scientists' involvement. Expanding areas of historical research are increasing demand for collections of multiple-edition old science textbooks – from kindergarten to advanced education. Biography and autobiography of scientists is collectible. Researchers in the fields of popular culture and science and culture are seeking collections of what used to be regarded as ephemera, such as science postcards, posters, leaflets, invitations to and menus from scientific congress banquets and conference programmes. Popular science written by non-scientists or written by scientists is now being studied. There are numerous possibilities for new areas of collecting specialization including ethology, science and society, science and government, science dictionaries, handbooks, or field guides, animal rights publications, poetry written by scientists or poetry written about science, or books of women scientists. The next edition of this work will surely expand to include new groups of collectors, collections, scholars and researchers. The desire to experience science through the special collections of individuals and libraries will not dissipate.

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Selective Index
of authors, printers, libraries and collectors

In a work of this nature there are innumerable references to certain figures and certain works and to index all of them would be otiose. With very few exceptions, titles of works are not indexed at all, since most works are mentioned within striking distance of the author him- or herself. This Index confines itself to those passages where an author's work or influence is discussed, or the presence of his works in a collection (or occasionally his own collection) is noteworthy, or again where a printer's role is the topic. Only a few subject headings are noted, but bibliographies of subjects are. There are two groupings within the Index, of Journals and of Printers/Publishers.